

Overview of the National Ignition Facility



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Presentation of the NIF Nuclear Astrophysics Workshop



Lawrence Livermore National Laboratory

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UCRL-PRES-234105



**Could we build a miniature
sun on earth?**



It seems likely!




**San Francisco
(45 mi.)**

Lawrence Livermore National Laboratory

National Ignition Facility



NIF-0605-10997-L47
27EIM/cld



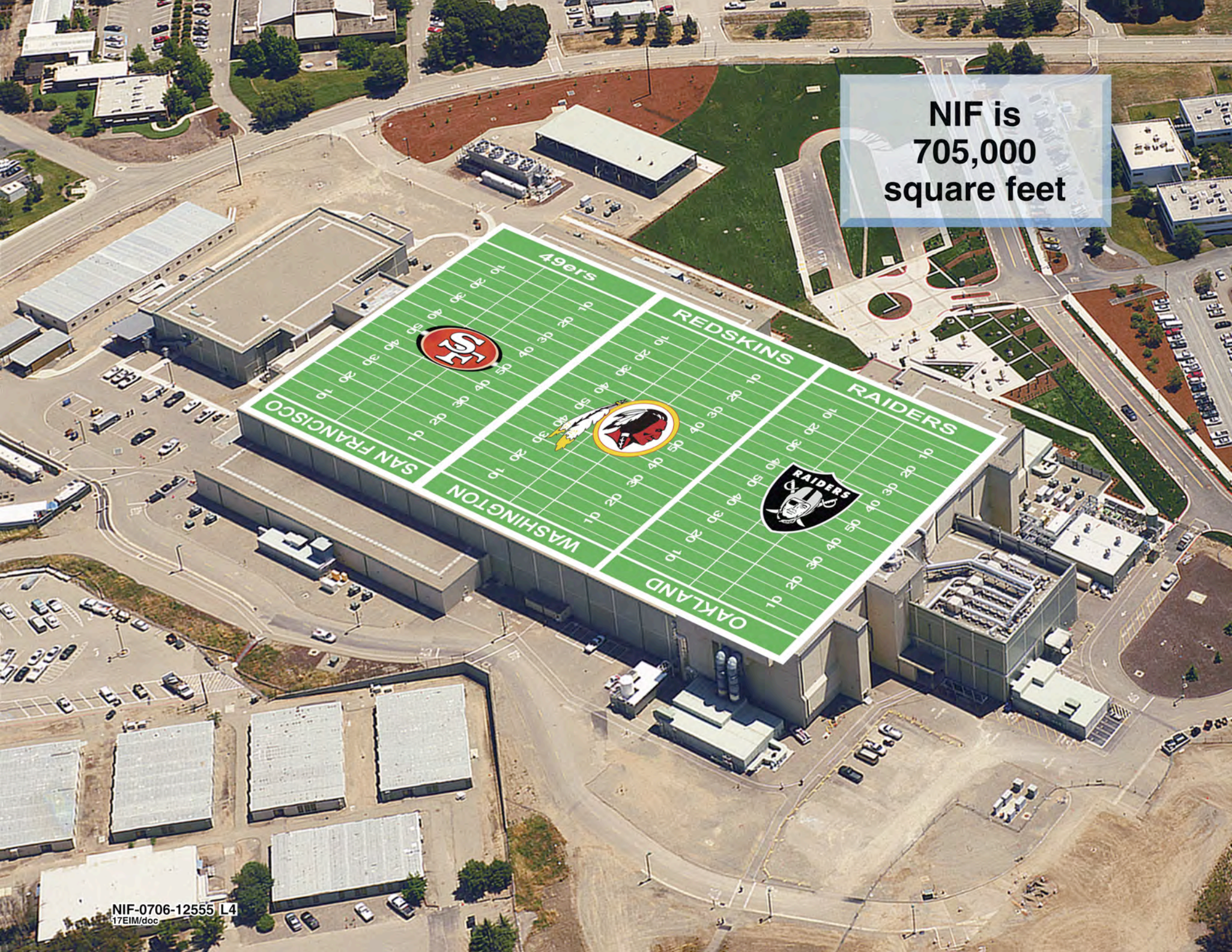
National Ignition Facility



NIF-0705-11159-L20

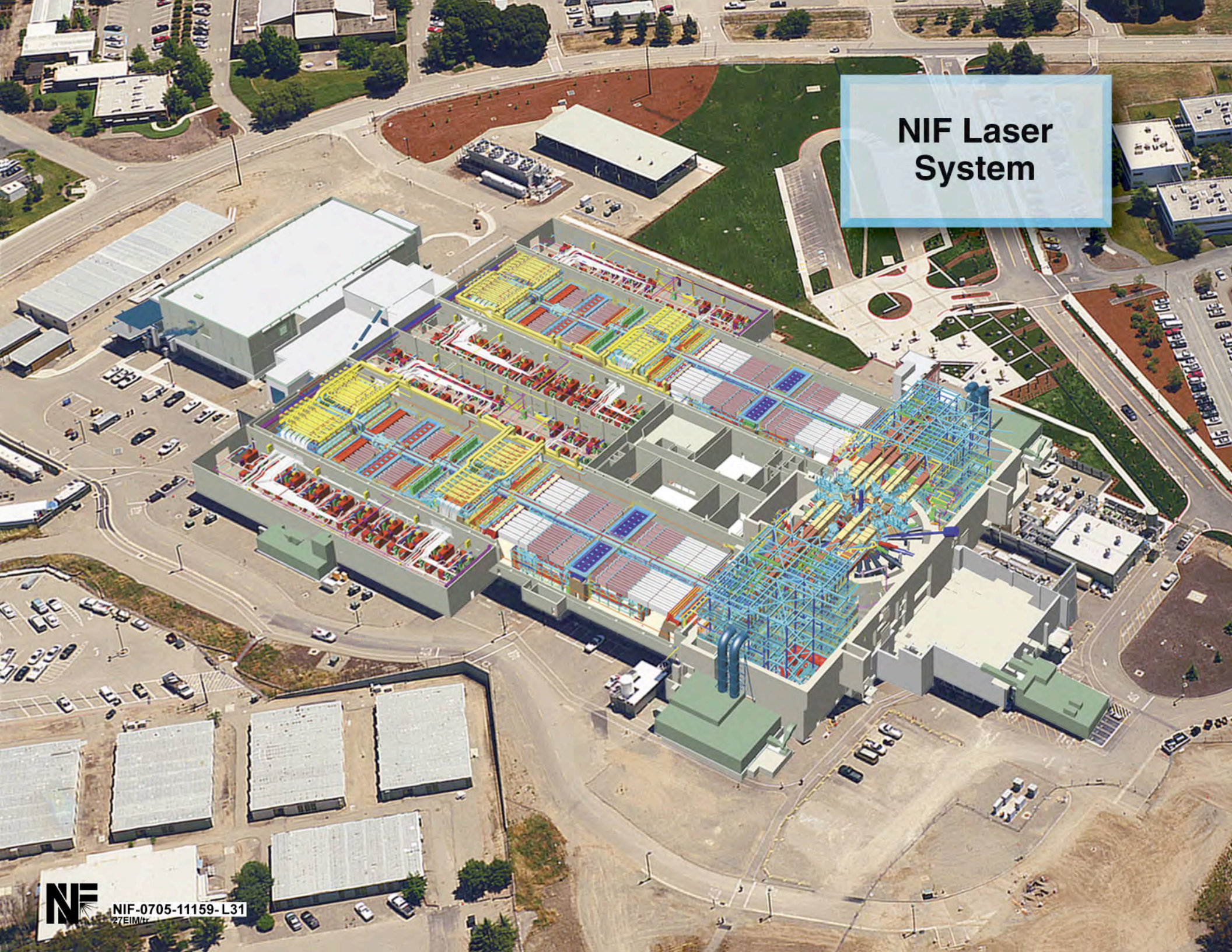
27EIM/vr

**NIF is
705,000
square feet**



**NIF is
70,000
square meters**





NIF Laser System

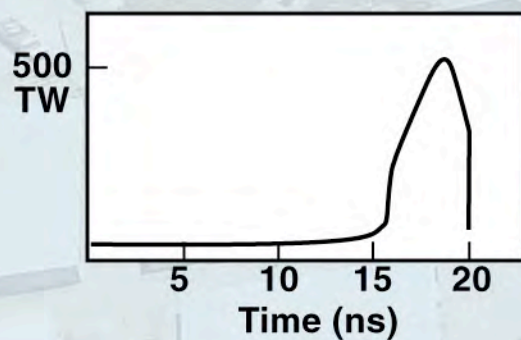


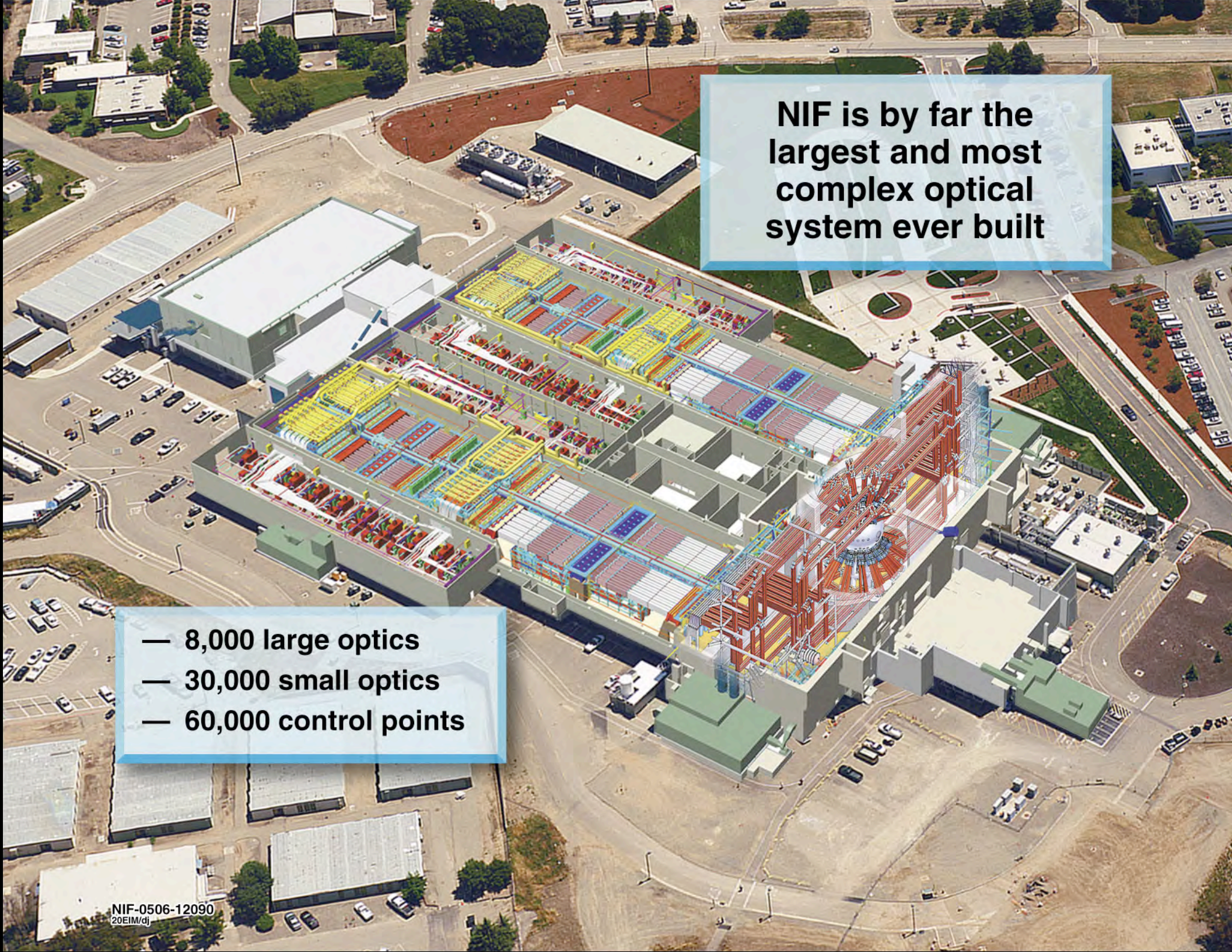
NIF-0705-11159-L31

27EIM/vr

NIF Laser System

- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm



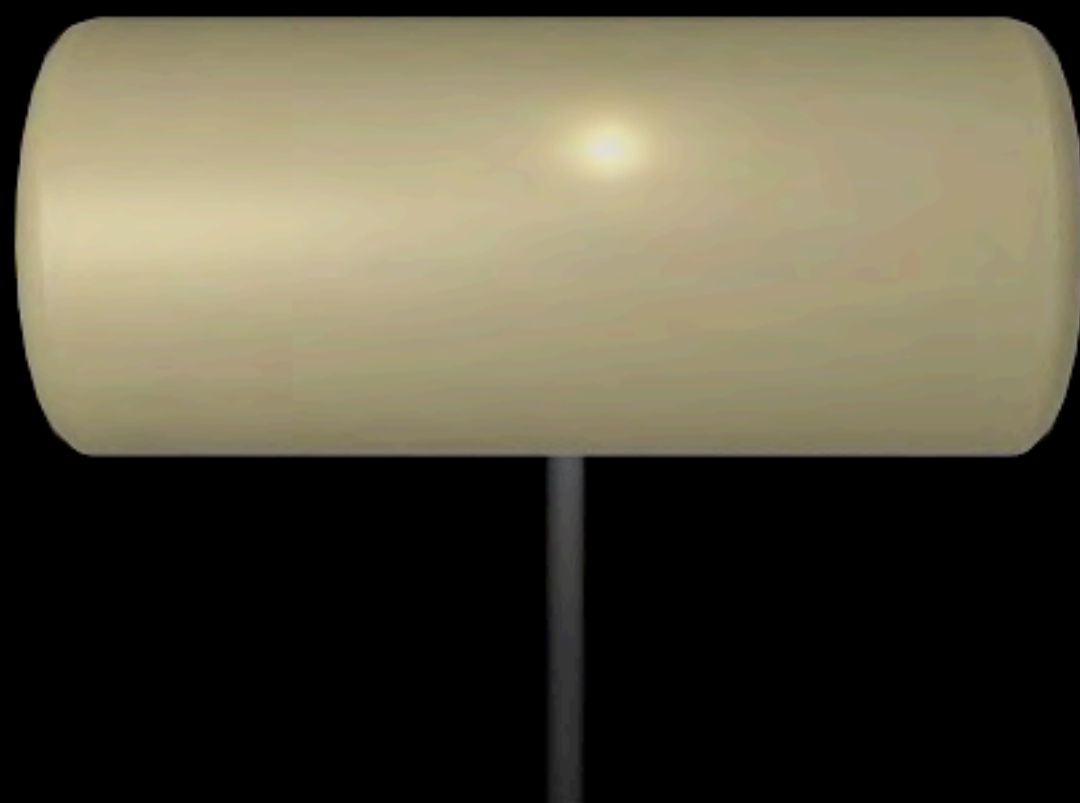


**NIF is by far the
largest and most
complex optical
system ever built**

- 8,000 large optics
- 30,000 small optics
- 60,000 control points

A close-up photograph of a person's eye. A surgical instrument, which has a cylindrical gold-colored head and a thin metal shaft, is positioned near the eye. The instrument's head is emitting a bright light, and a small, dark, circular object is visible on the cornea. The eye is blue, and the surrounding skin is light-colored. The instrument is held by a hand, which is visible at the bottom of the frame.

**Ignition
Target**





NIF appears to be the culmination of a long line of glass laser systems

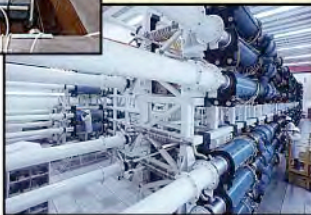
Janus

100J IR



Shiva

10kJ IR



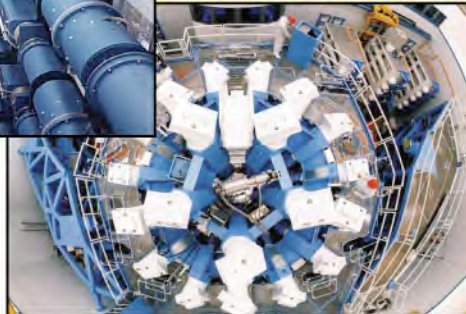
Nova

30kJ UV



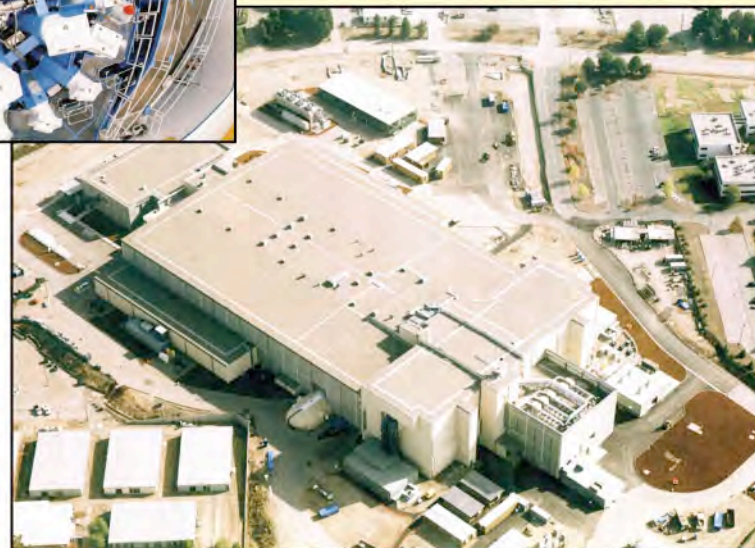
Omega

25kJ UV

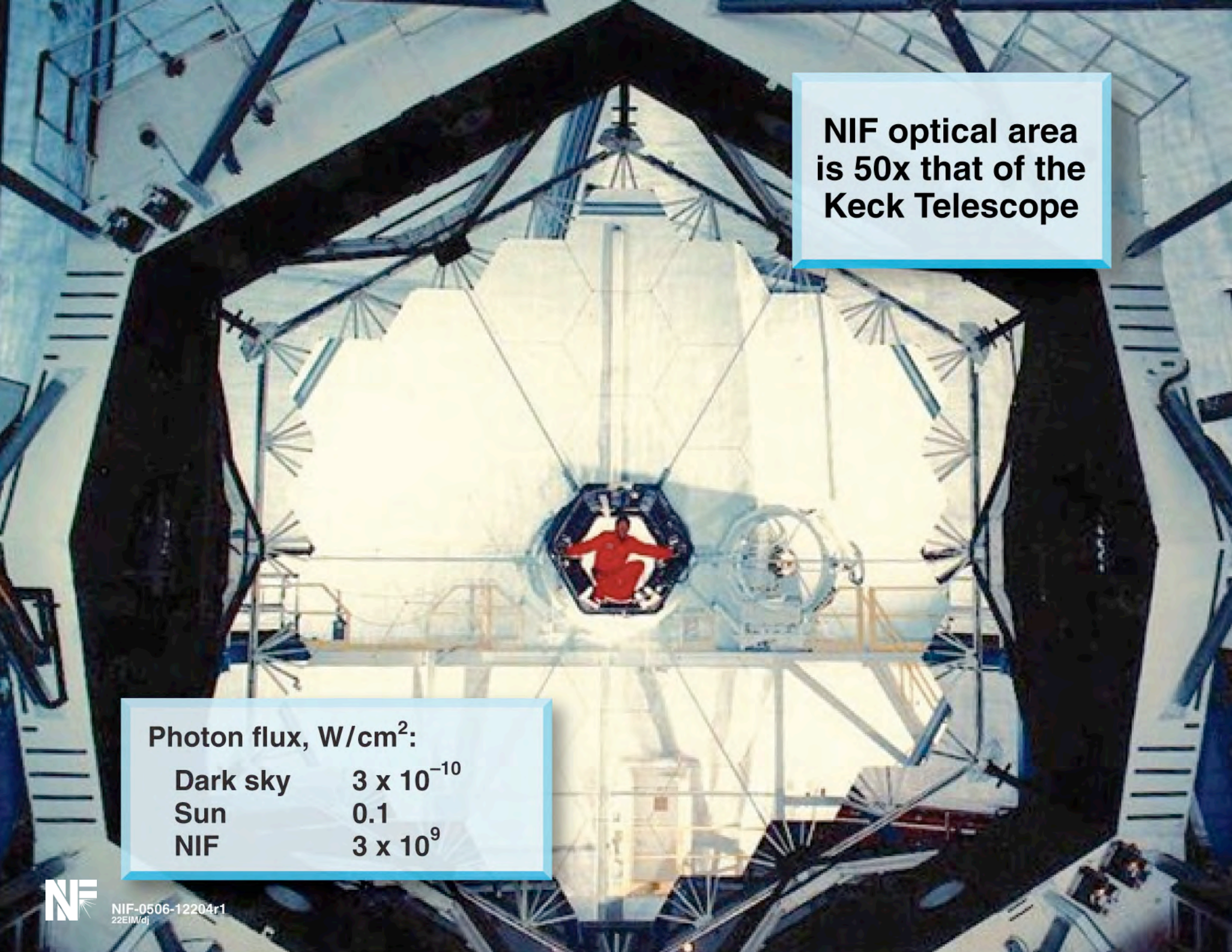


NIF

1.8MJ UV



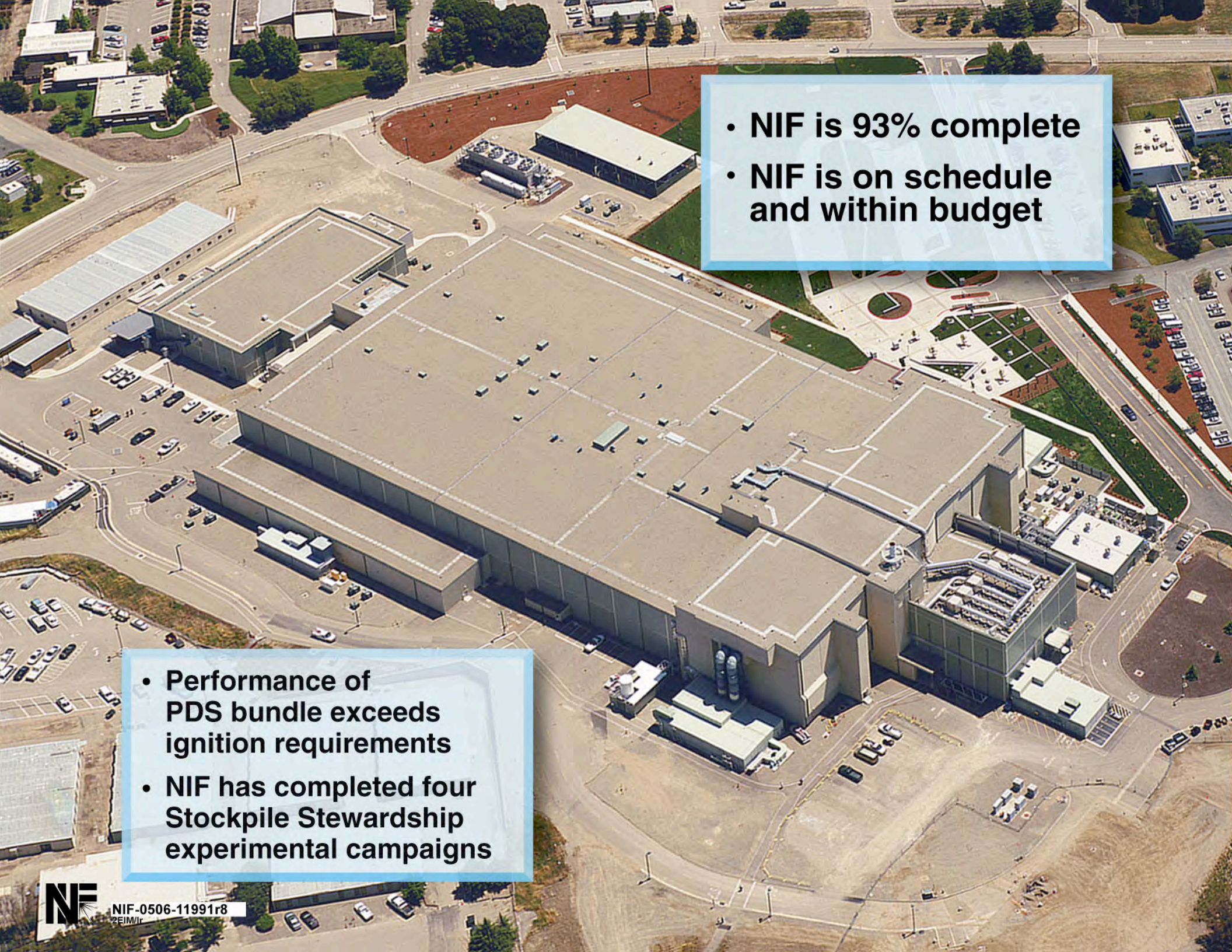
NIF is designed to meet all mission requirements



NIF optical area
is 50x that of the
Keck Telescope

Photon flux, W/cm²:

Dark sky	3×10^{-10}
Sun	0.1
NIF	3×10^9

- 
- NIF is 93% complete
 - NIF is on schedule and within budget

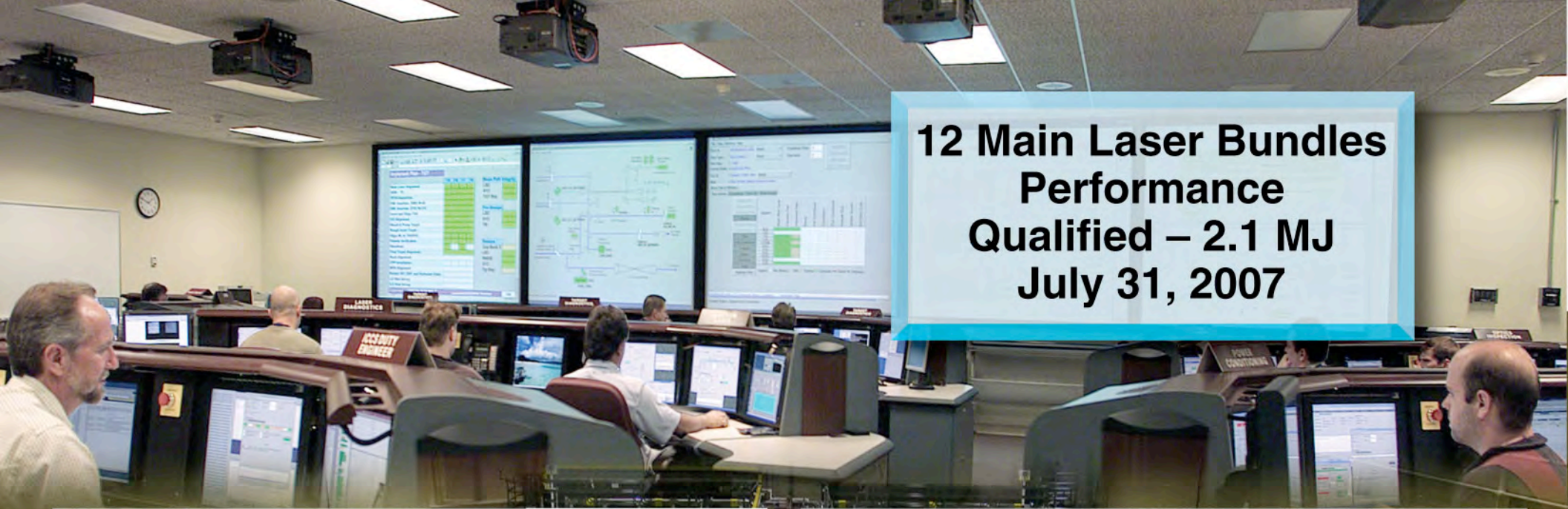
- Performance of PDS bundle exceeds ignition requirements
- NIF has completed four Stockpile Stewardship experimental campaigns



NIF-0506-11991r8

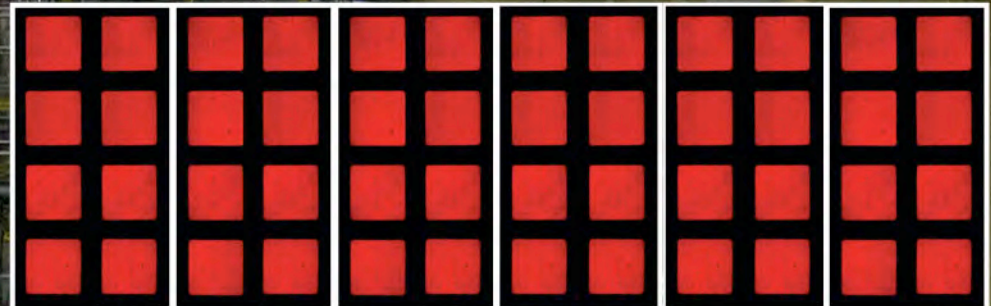
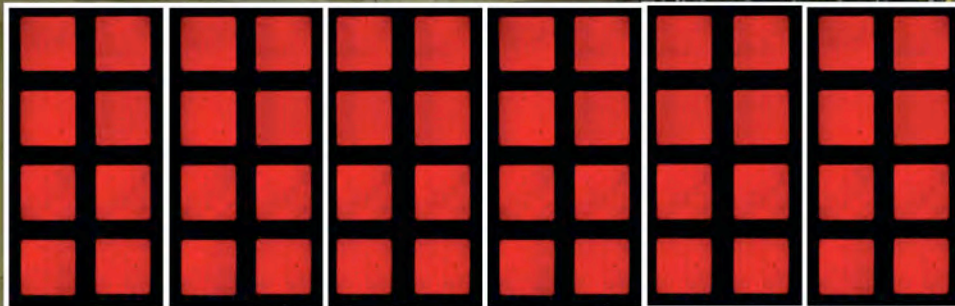
Laser Bay 2





12 Main Laser Bundles
Performance
Qualified – 2.1 MJ
July 31, 2007

The image shows a control room with several operators seated at desks with multiple computer monitors. Large projection screens at the front of the room display technical data and diagrams. The room is well-lit with overhead fluorescent lights.



Laser Bay 2
Commissioning
Complete

The image shows a long, narrow bay filled with numerous white, cylindrical laser components arranged in rows. The bay is illuminated by overhead lights, and the components are connected by various cables and structural elements.

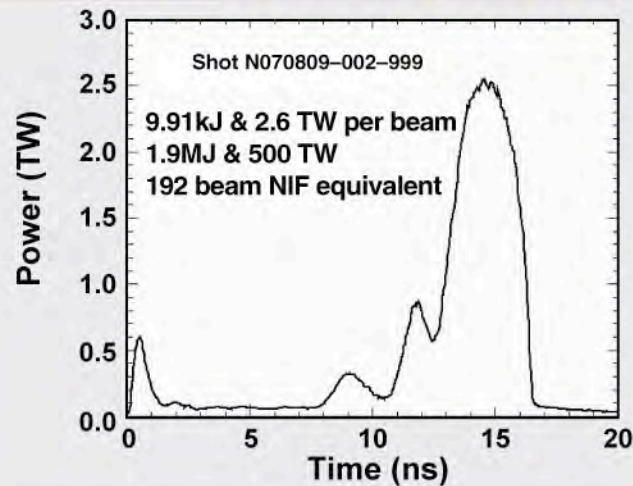
World's Highest
Energy Laser



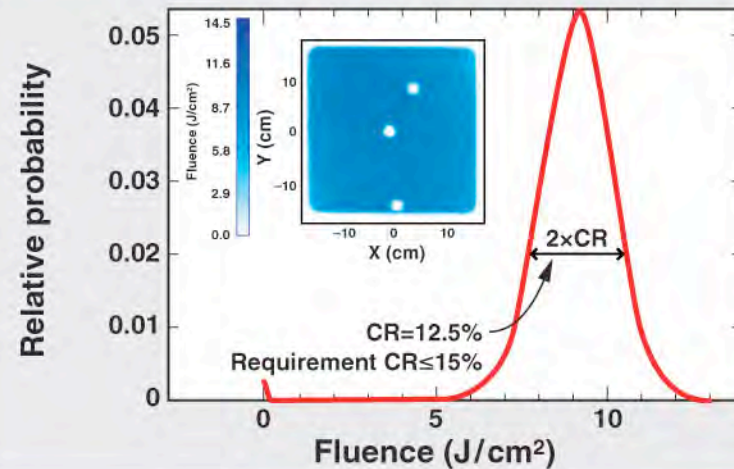
NIF-0407-13482r9
06BVW/mfm

NIC 1.8 MJ ignition point design, energy, power, pulse shape & smoothing were achieved simultaneously

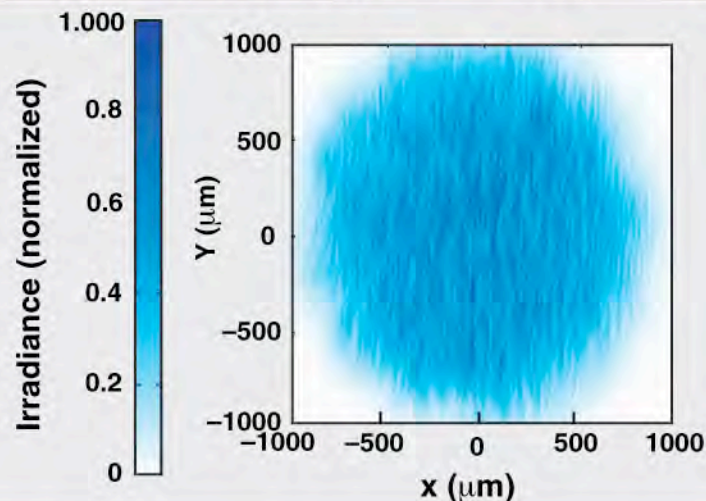
3ω Pulse Shape (500 TW)



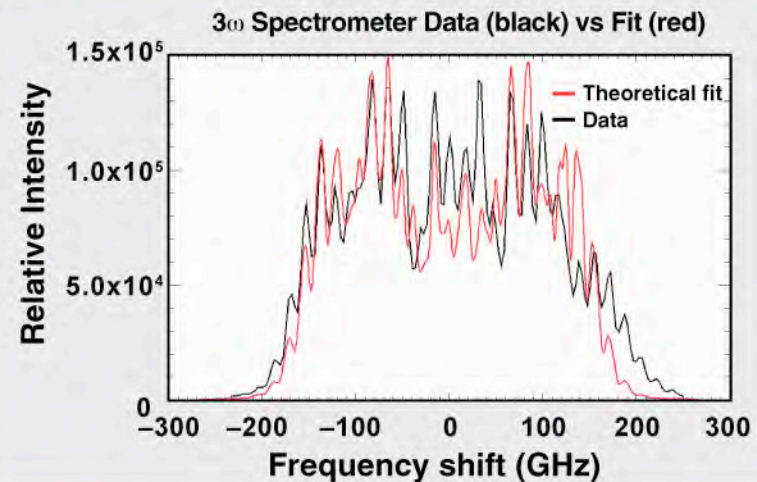
3ω Near Field Profile



3ω Focal Spot ($1.91 \times 1.64 \text{ mm}^2$)



3ω SSD Bandwidth (270 GHz)

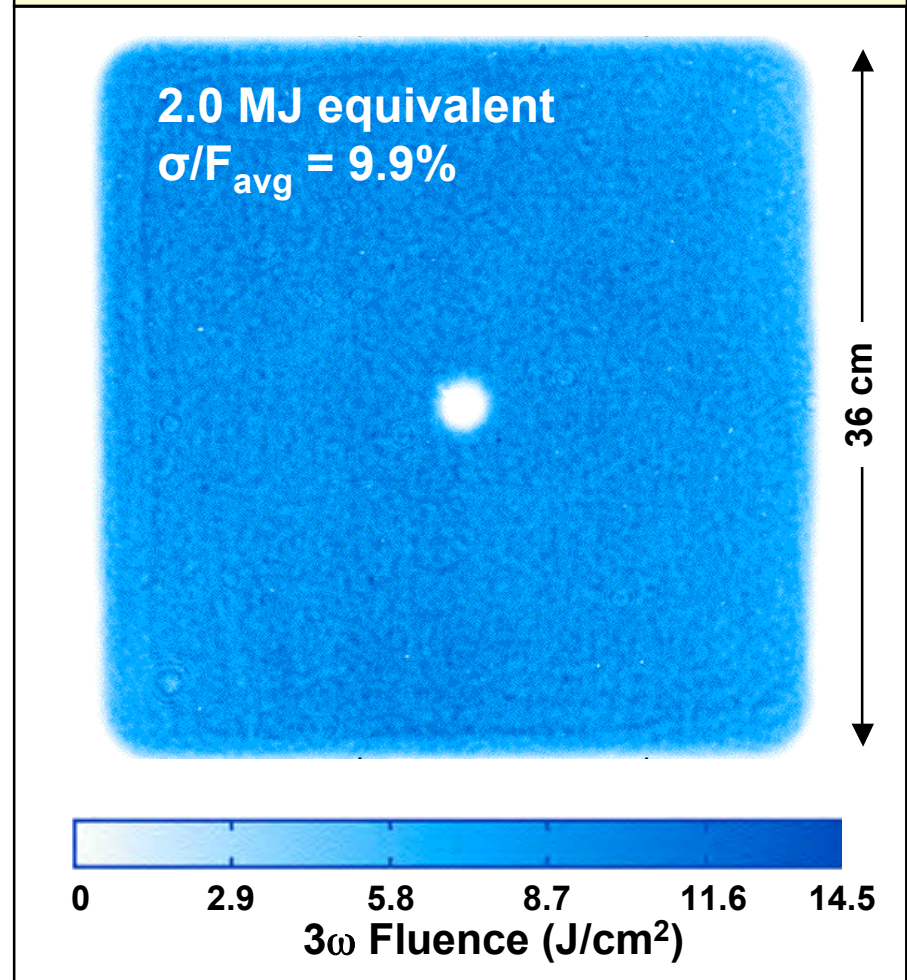


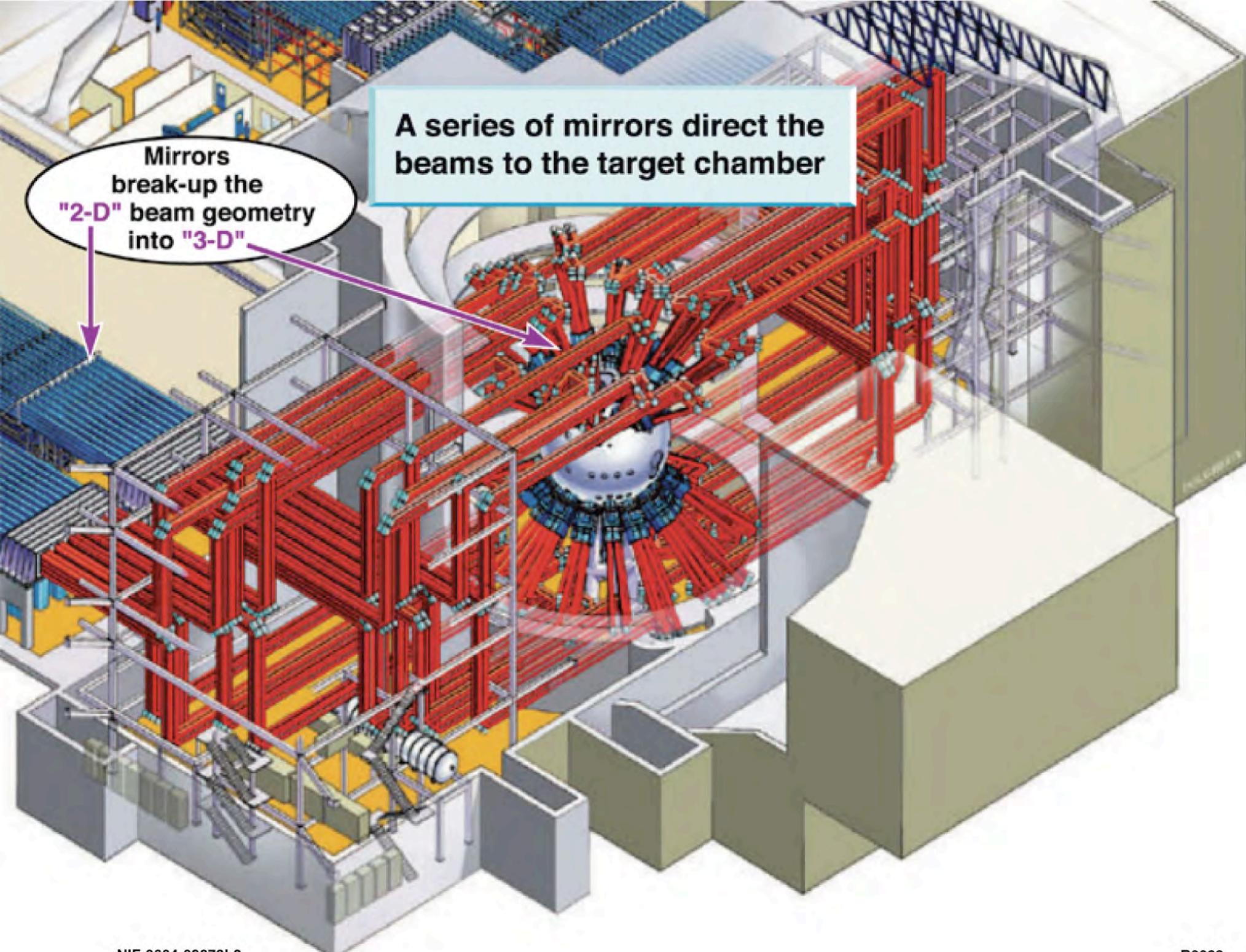
>20 shots at full energy have been demonstrated

**Final Focus lens
after 11 shots at > 1.6 MJ**



**Shot N060329-003-999
11th shot at > 1.6 MJ**





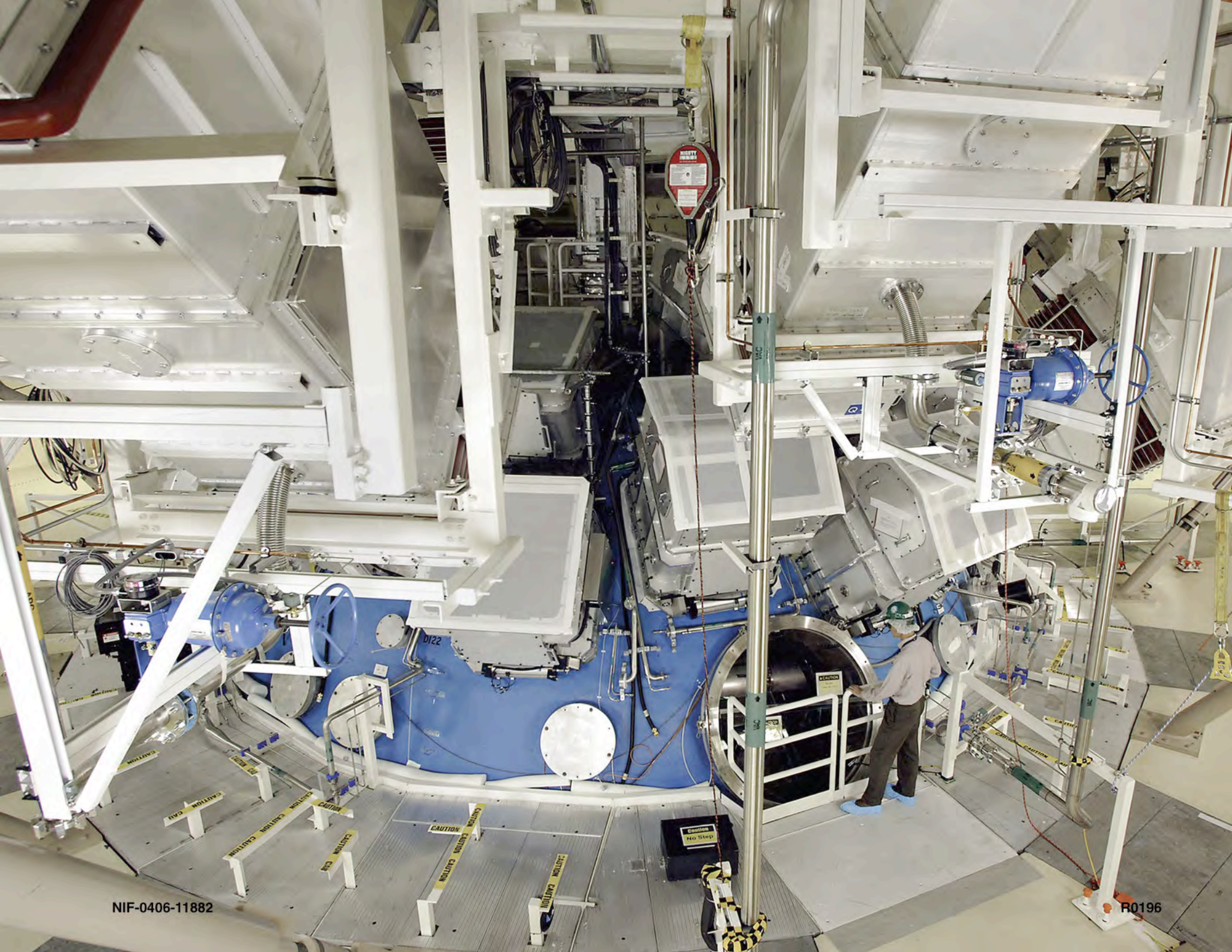
A series of mirrors direct the beams to the target chamber

Mirrors break-up the "2-D" beam geometry into "3-D"



Switchyard 2

Target Chamber



NIF-0406-11882

R0196

A photograph of the interior of a target chamber, showing a complex arrangement of metallic components, including a central target area and numerous surrounding diagnostic ports or sensors. The chamber is illuminated with a mix of green and purple light. A blue rectangular box in the upper right corner contains the text "Target Chamber Interior".

Target Chamber Interior



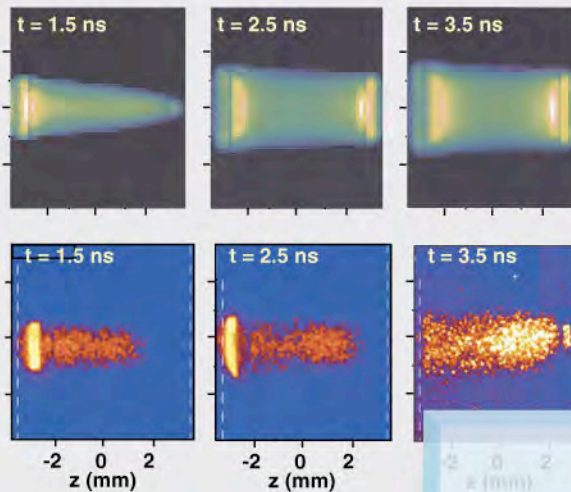
Target Chamber



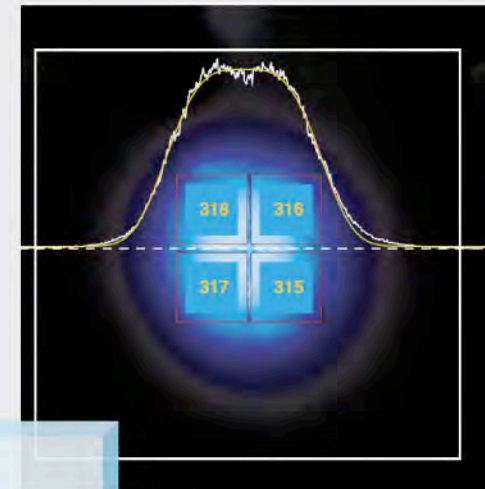
**Ignition Plan has 35
distinct diagnostic
requirements**

- 13 requirements were met by systems fielded on NEL
- 98% channel reliability in NEL experiments

LPI

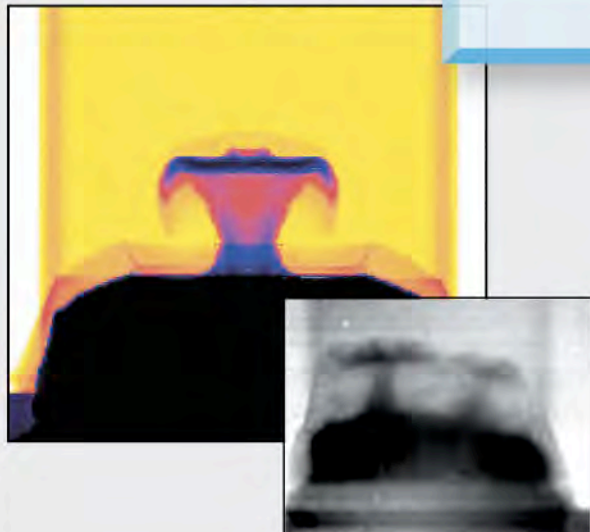


Hohlraums

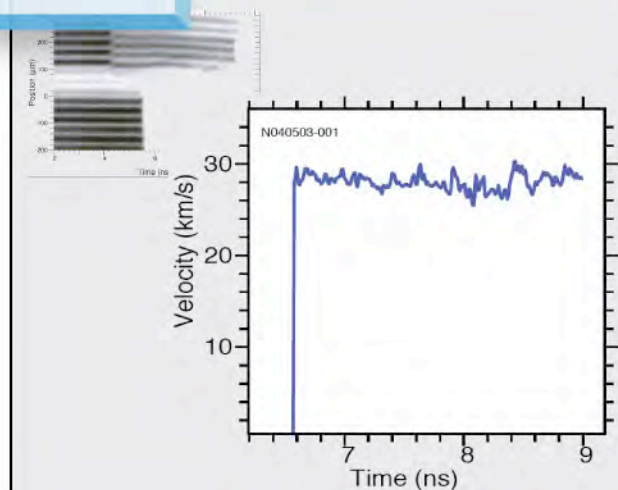


**NIF is steadily
developing a large range
of experimental
capabilities**

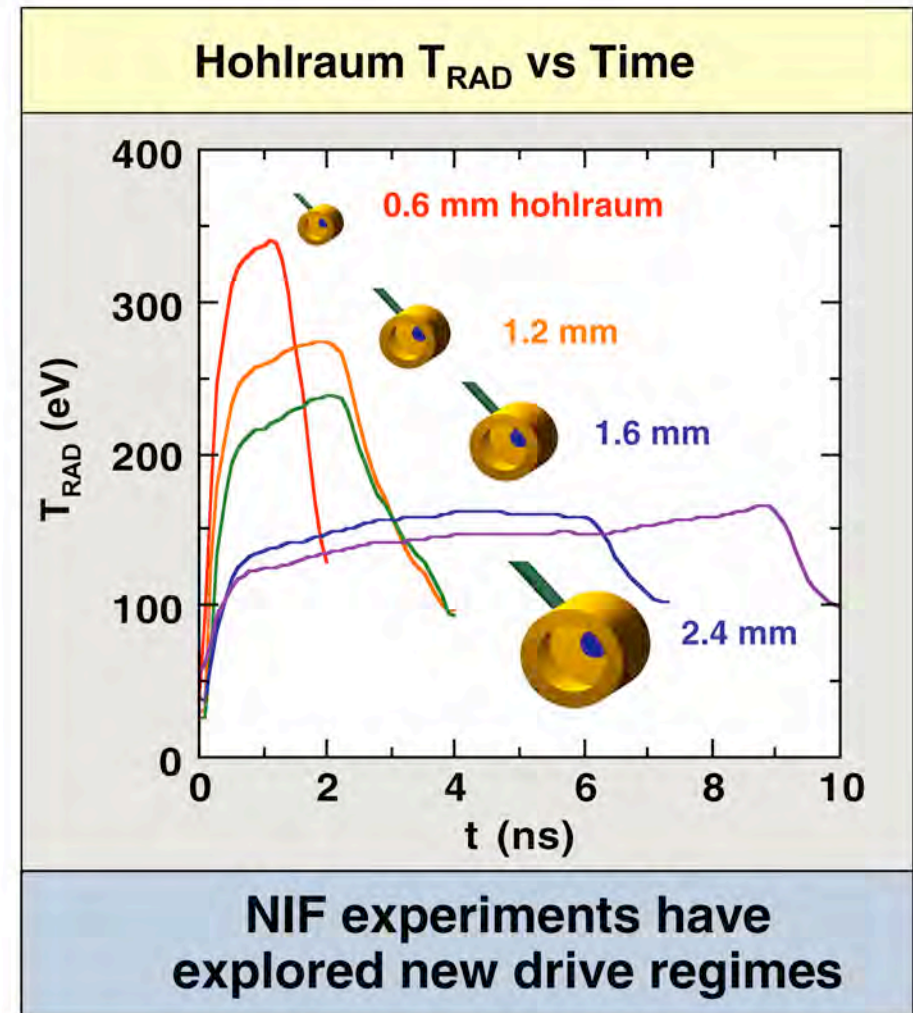
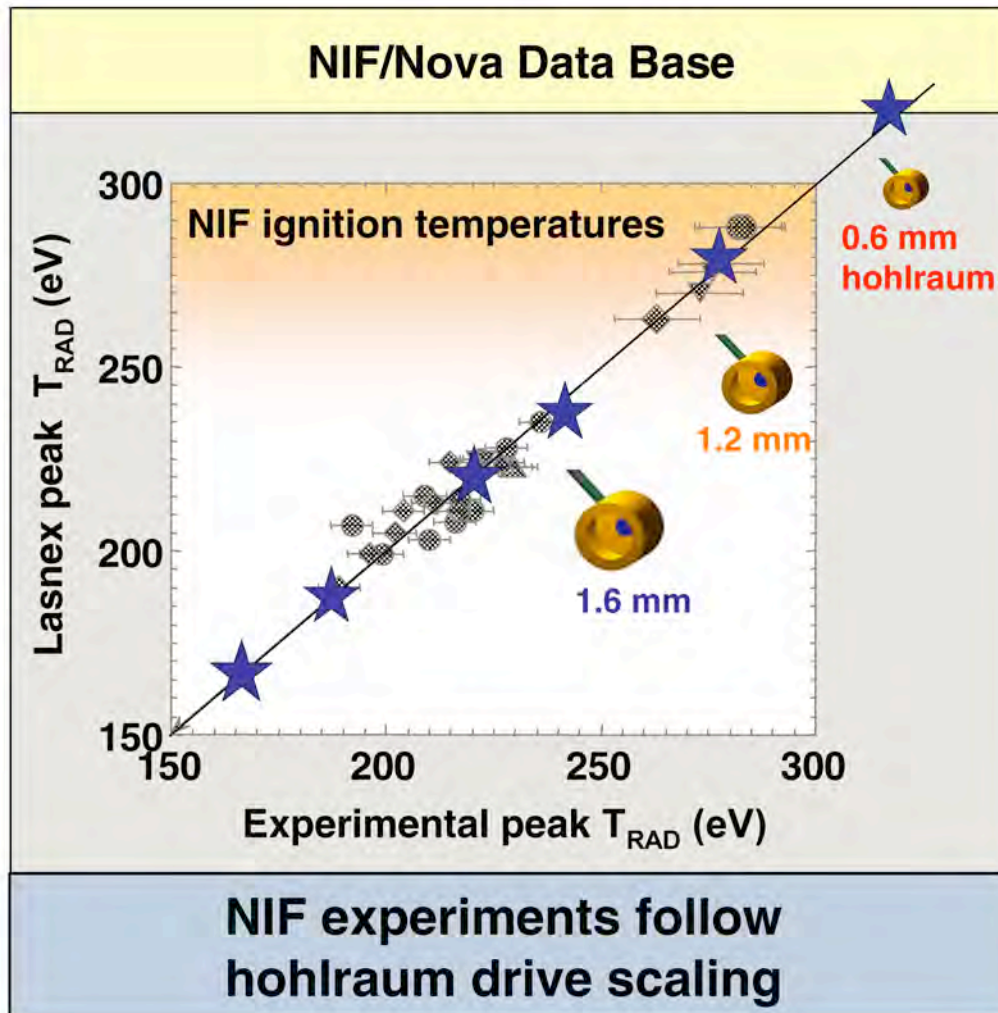
Hydro



EOS



Our first hohlraum experiments on NIF have measured drive beyond the Nova data base (exceeding 300 eV)

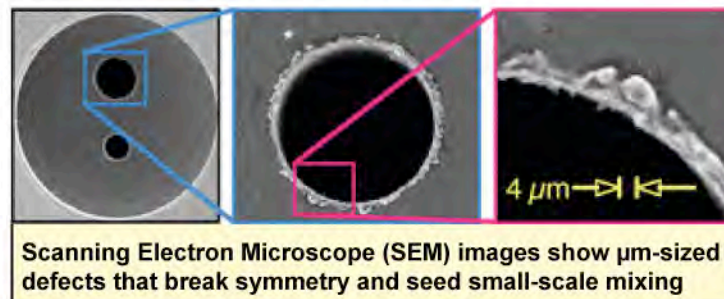


The complexities of the dual jet interaction challenge our modern hydrodynamics codes

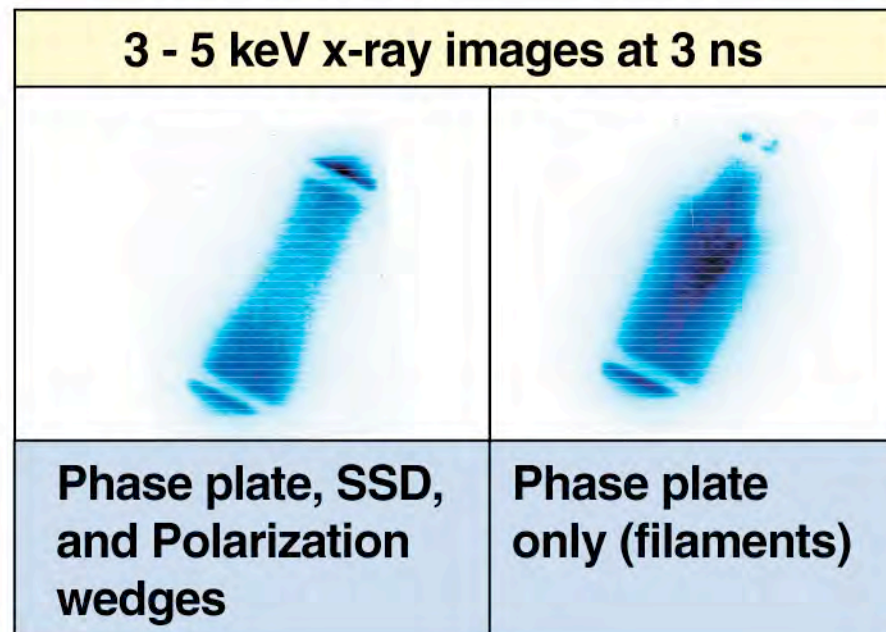
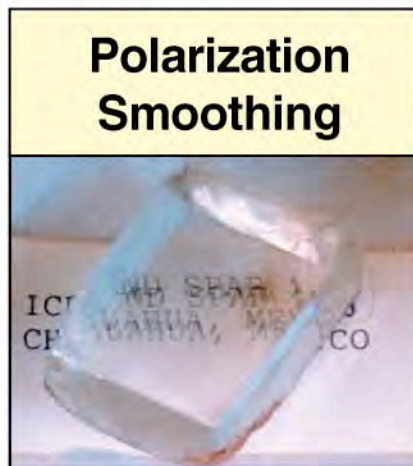
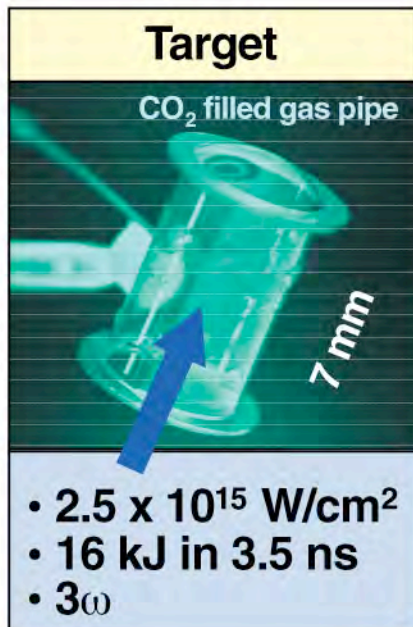
Asymmetrical Dual Jets



- As part of NIF Hydro Campaign, LANL conducted dual jet experiments
- 3D RAGE simulations show many quantitative similarities with data
- However, smaller-scale details are not fully captured
- This is attributed to small scale target defects that break symmetry early in the jet's evolution



The first LPI experiments on NIF have demonstrated propagation in NIF ignition-scale plasmas

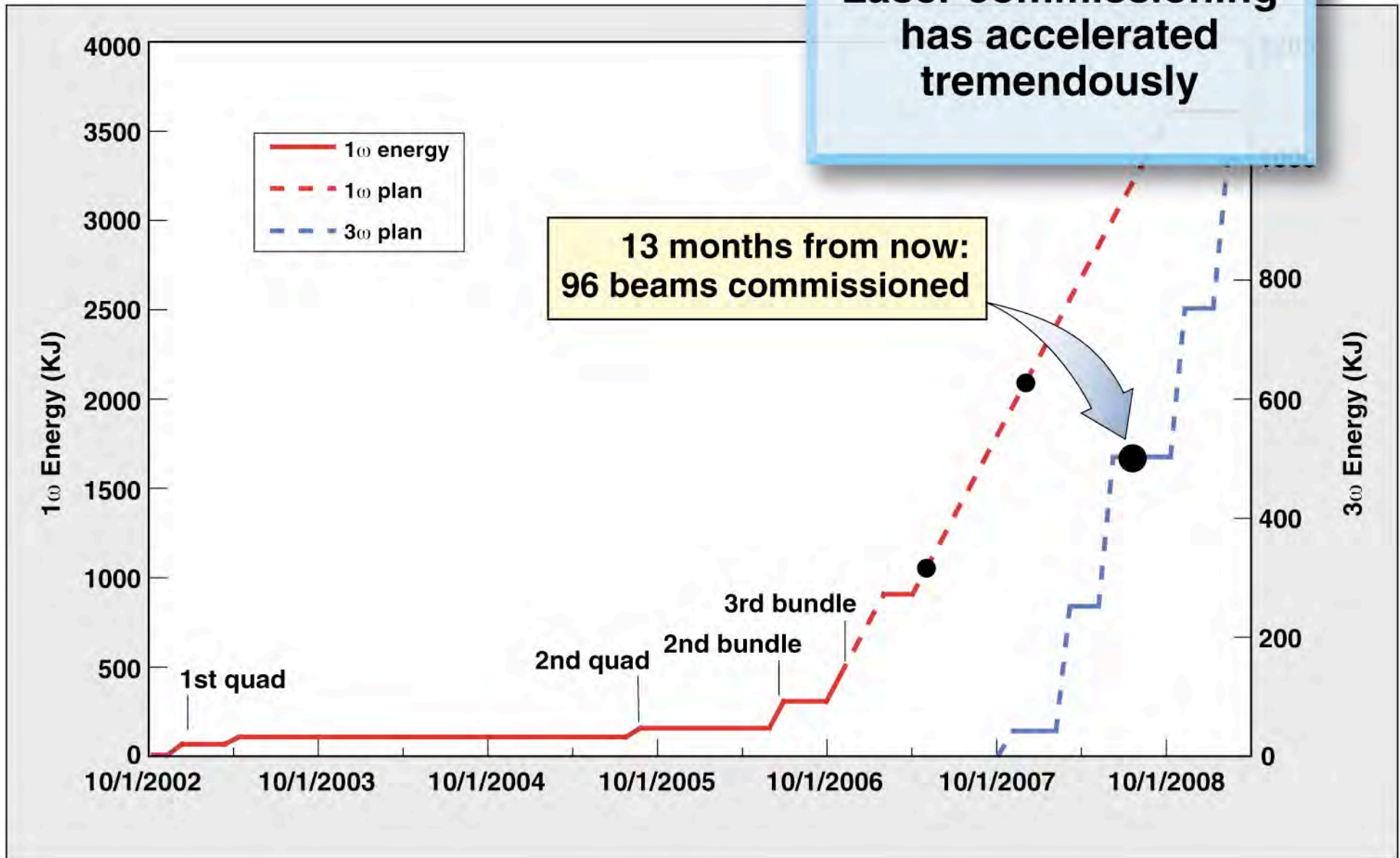


Propagation improvement consistent with modeling and increase in filamentation threshold with improved beam smoothing (i.e., less power/speckle)

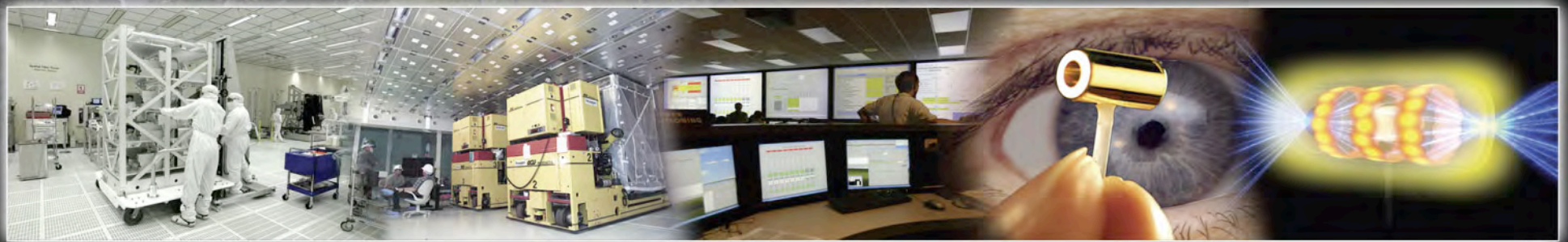
S. Glenzer (10186)
E. Dewald (This Session)

**Laser commissioning
has accelerated
tremendously**

**13 months from now:
96 beams commissioned**



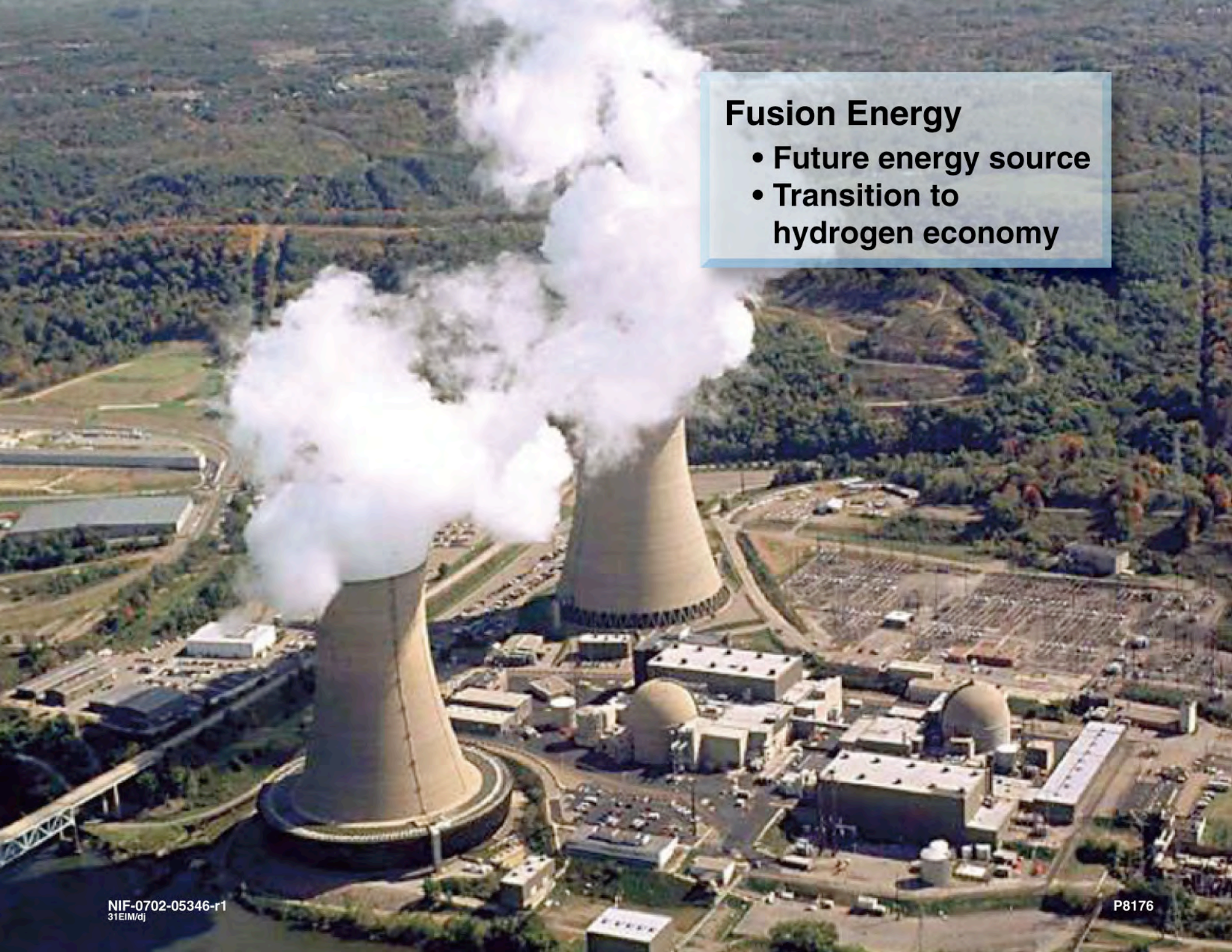
Why Are We Building NIF?



An aerial photograph of a vast, arid desert landscape. The terrain is characterized by numerous circular, crater-like pits of varying sizes, some filled with dark material. A light-colored, winding road or path cuts through the desert, leading towards a small cluster of industrial or storage structures on the right side. In the background, a range of low mountains is visible under a clear sky.

Stockpile Stewardship

Understanding the Cosmos



Fusion Energy

- Future energy source
- Transition to hydrogen economy

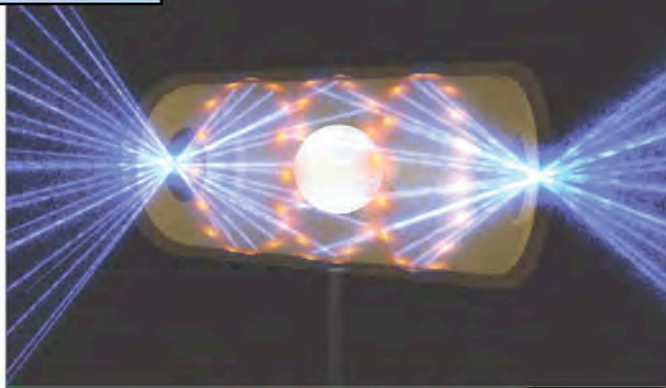
NIF Project



Completion in 2009

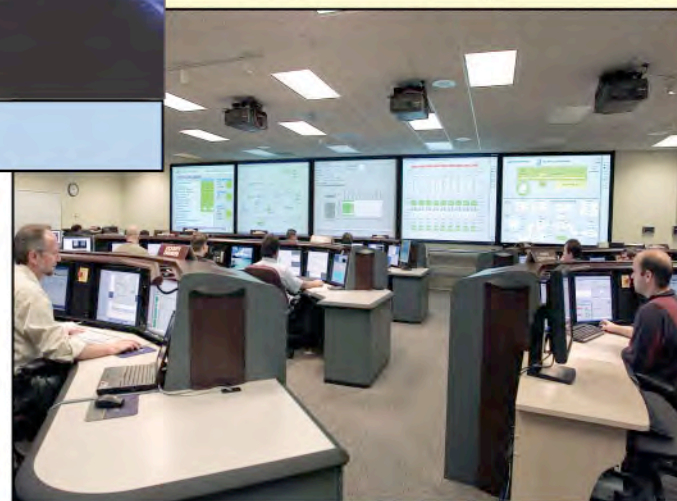
NIF Master Strategy

National Ignition Campaign



2006—2012

National User Facility



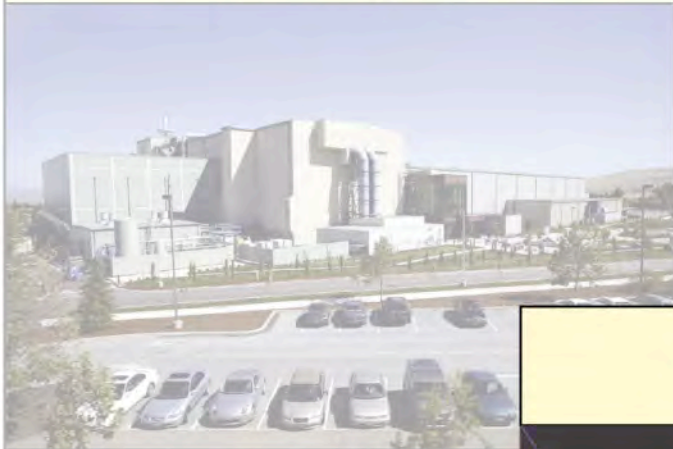
2009—2030

After 47 years, all of the pieces for ignition are nearly in place



- **The NIF laser and the equipment needed for ignition experiments, including high quality targets, will be available in 24 months**
- **We have an ignition point design target near 1 MJ with a credible chance for ignition during early NIF operations**
- **We have an Early Opportunity Shots (EOS) system commissioning campaign with 96 beams planned to start in 12 months**
- **The initial ignition experiments will only scratch the surface of NIF's potential, which includes high yields with green light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition in Fast Ignition (FI)**

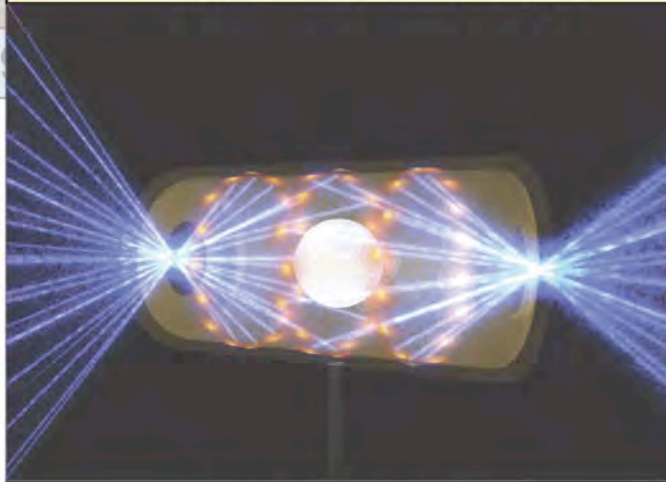
NIF Project



Completion in 2009

**The goal of NIC is
thermonuclear burn in
the laboratory with a
credible campaign
in 2010**

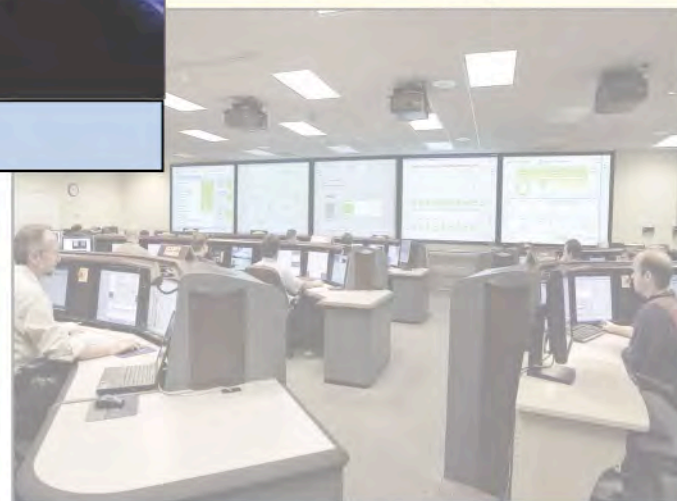
National Ignition Campaign



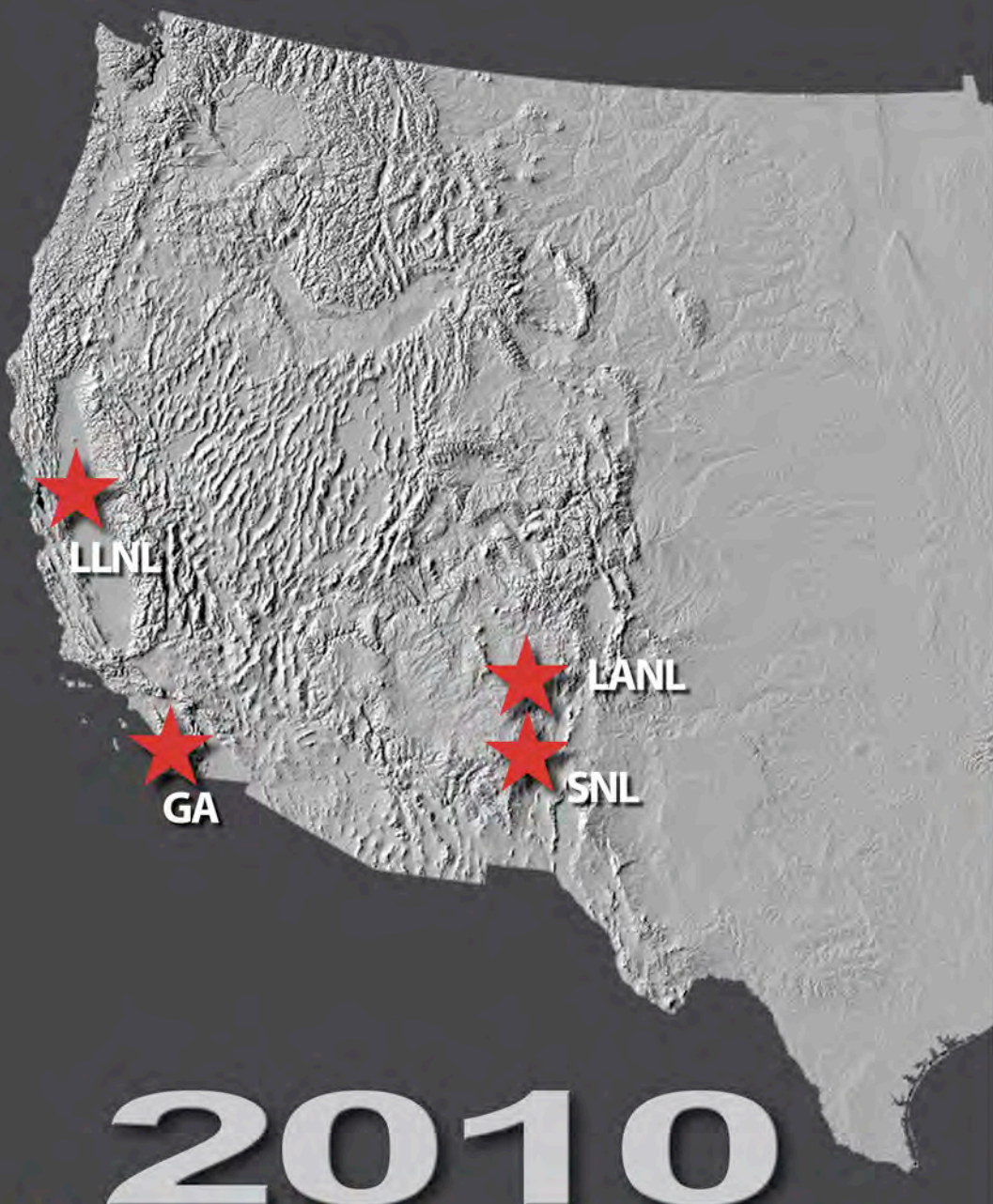
2006—2012

**NIC is the bridge from
NIF to routine operations
of a highly flexible HED
science facility**

National User Facility

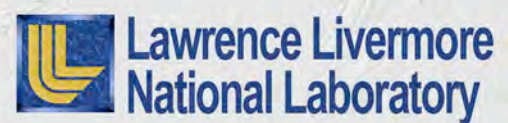
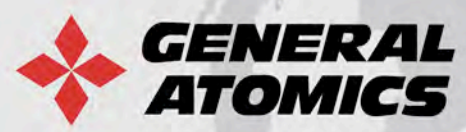


2009—2030



2010

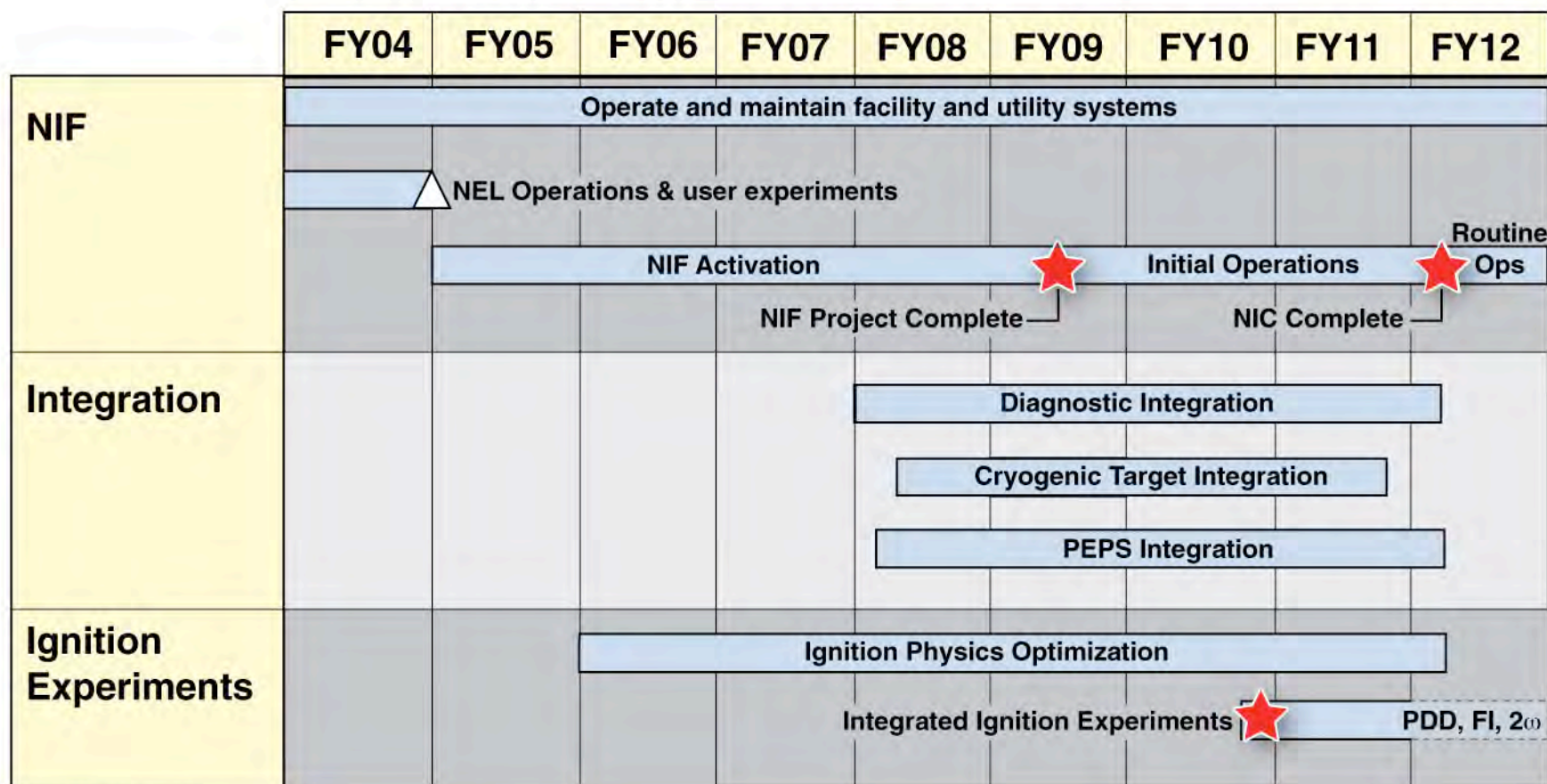
NATIONAL IGNITION CAMPAIGN



NIF/NIC Schedule

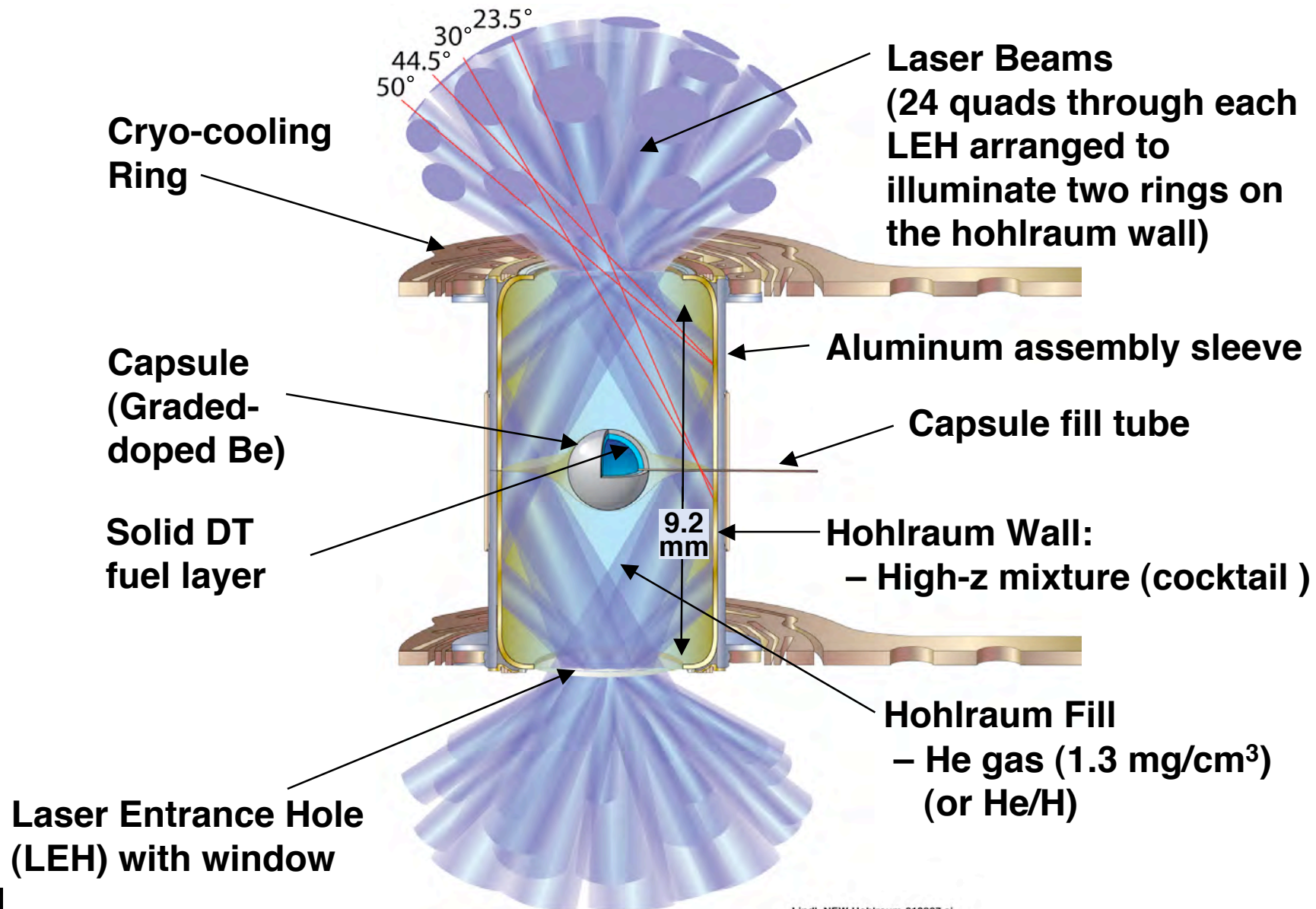


The National Ignition Campaign



NIF-0805-11232r11
16EIM/dj

The NIF point design has a graded-doped, beryllium capsule in a $U_{0.75}Au_{.25}$ hohlraum driven at 300 eV

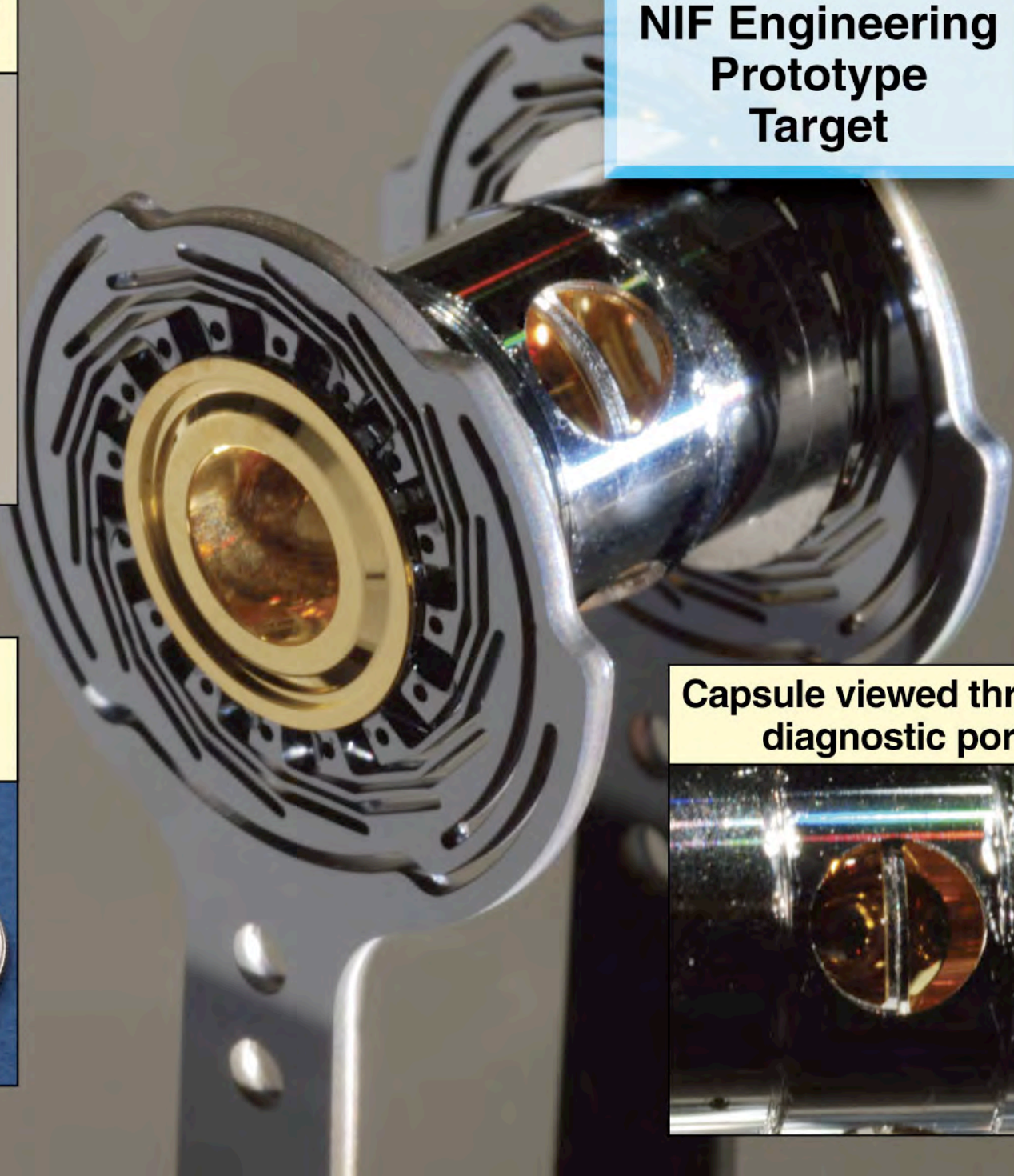


Lindl_NEW-Hohlraum-012307.ai

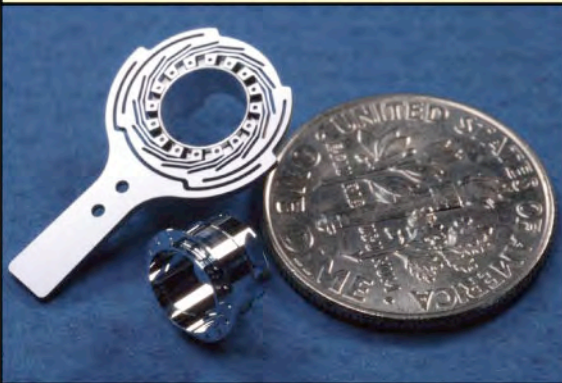
**Aluminum Thermal Can
and Cocktail Hohlräum**



**NIF Engineering
Prototype
Target**



**Silicon Cooling Ring
and Thermal Package
Component**



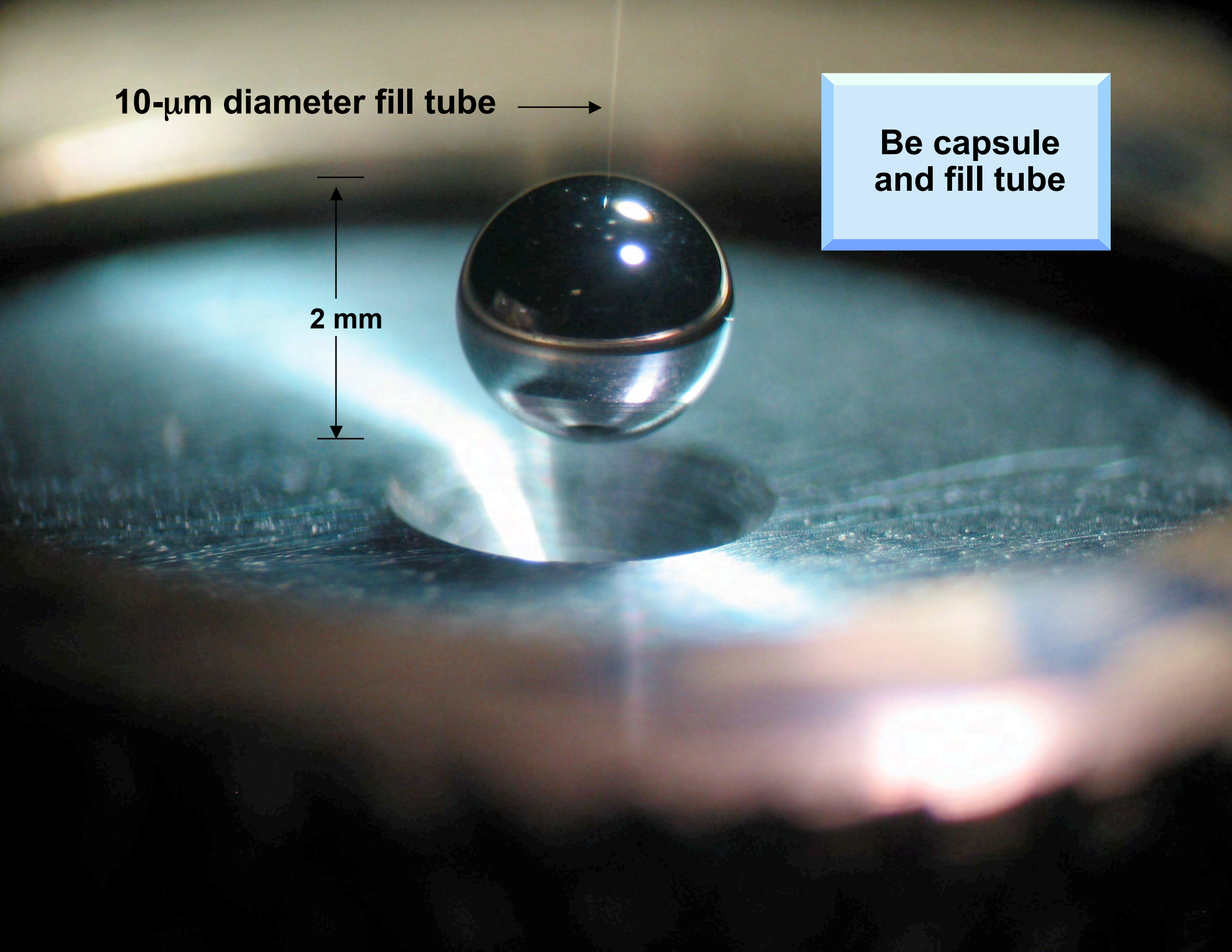
**Capsule viewed through
diagnostic port**

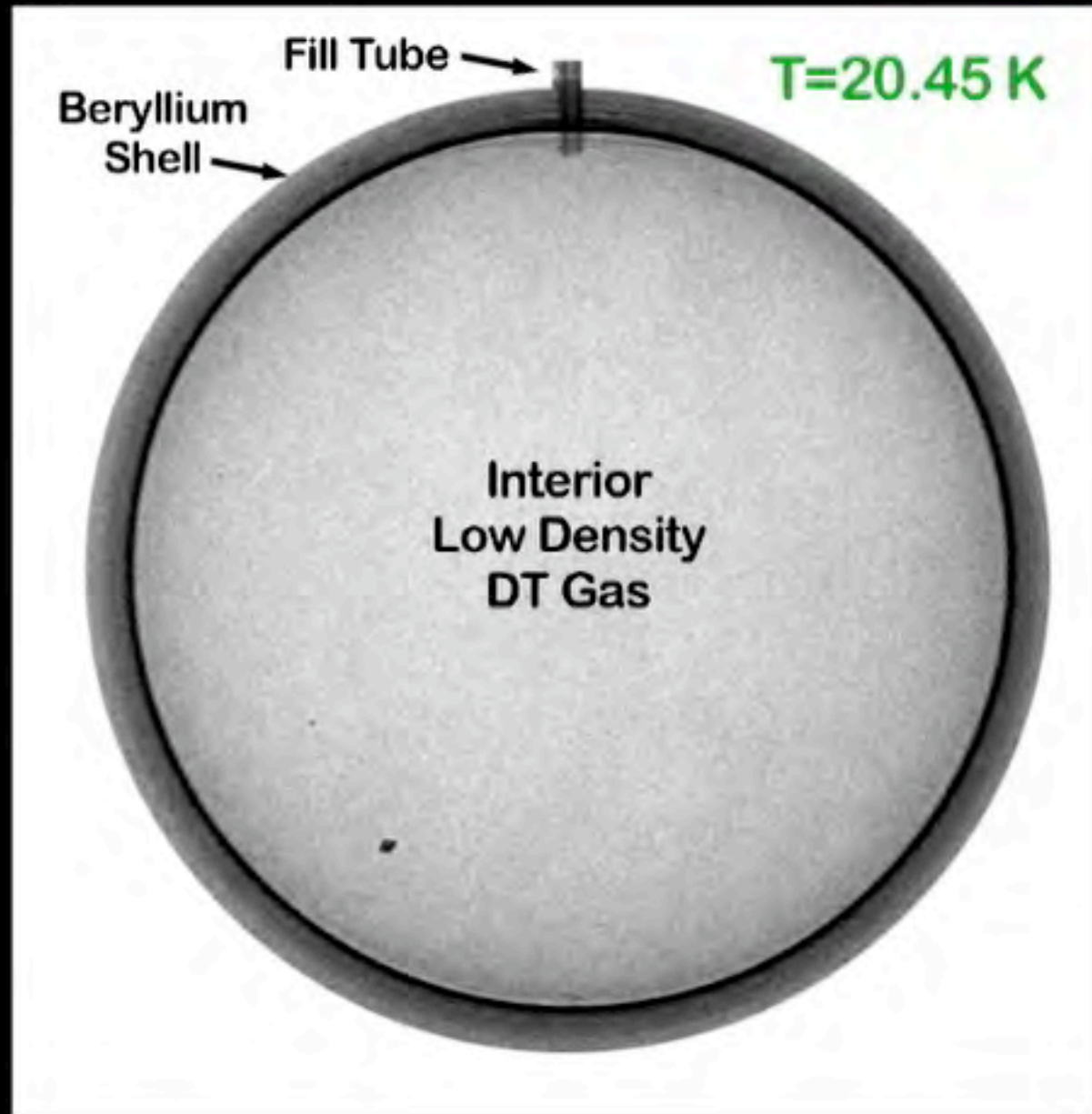


10- μ m diameter fill tube \longrightarrow

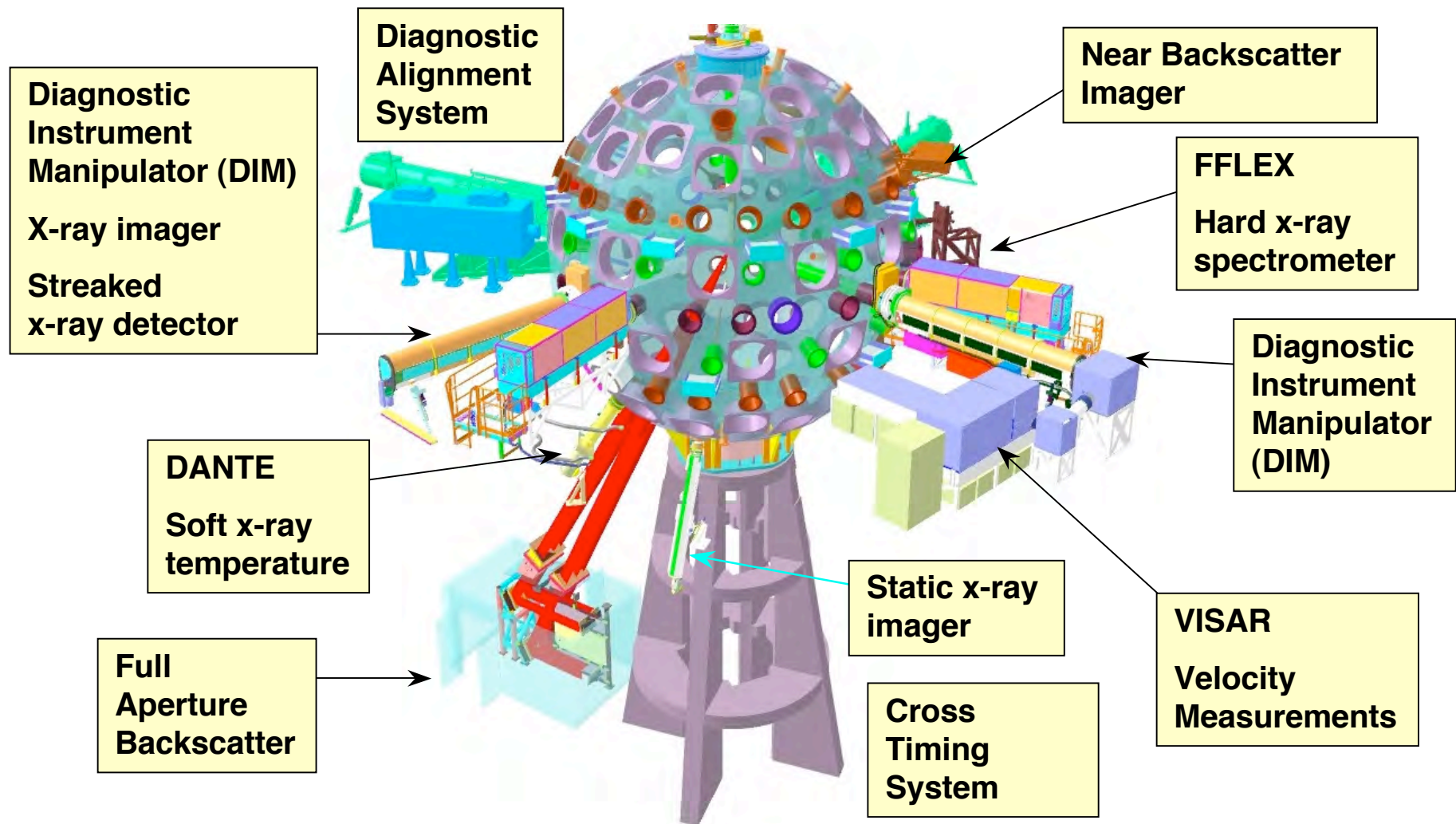
2 mm

Be capsule
and fill tube



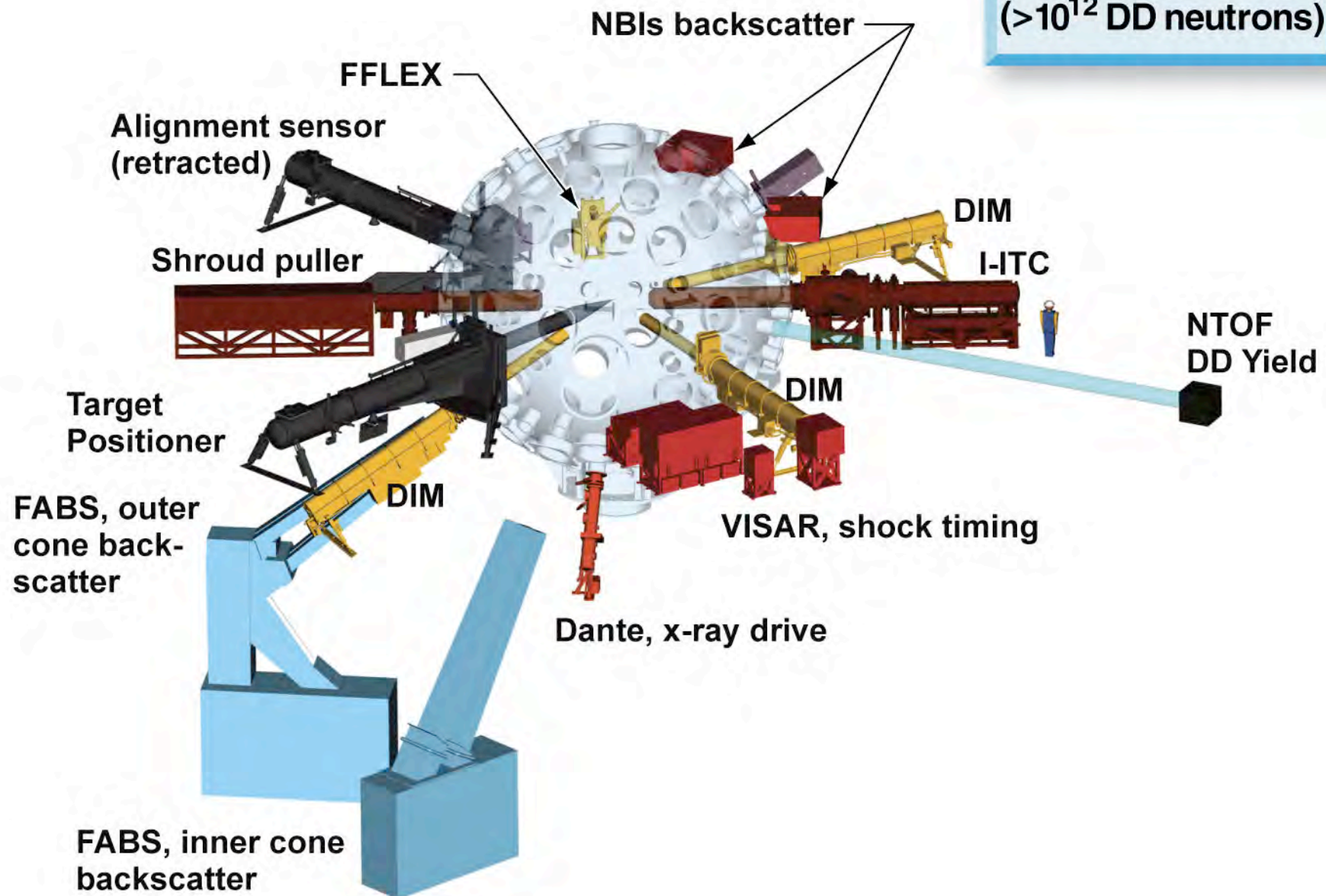


We have 30 types of diagnostic systems planned for NIF



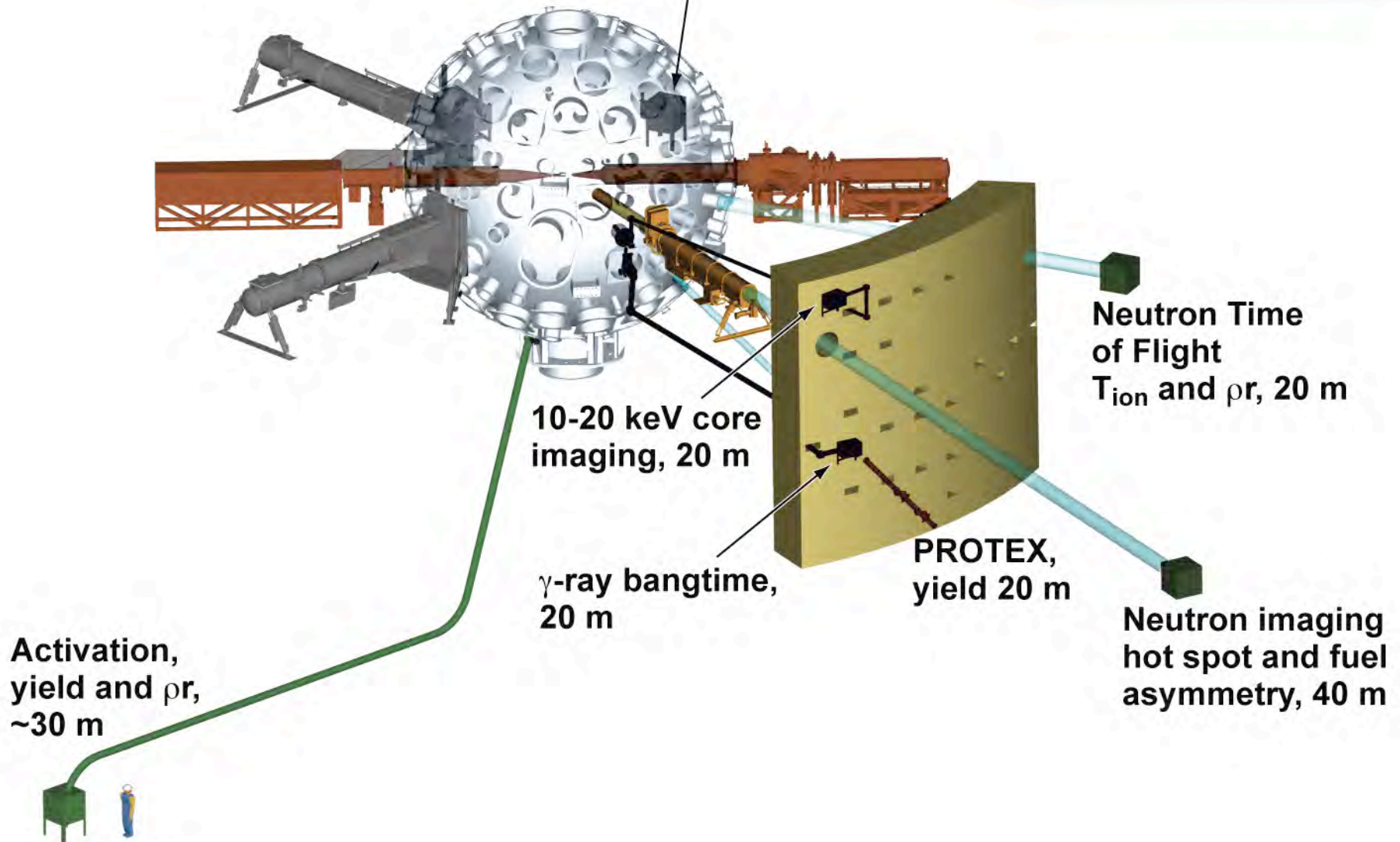
We successfully fielded ~ half of all the types of diagnostic systems on NIF

**Low Yield
Diagnostics
($>10^{12}$ DD neutrons)**



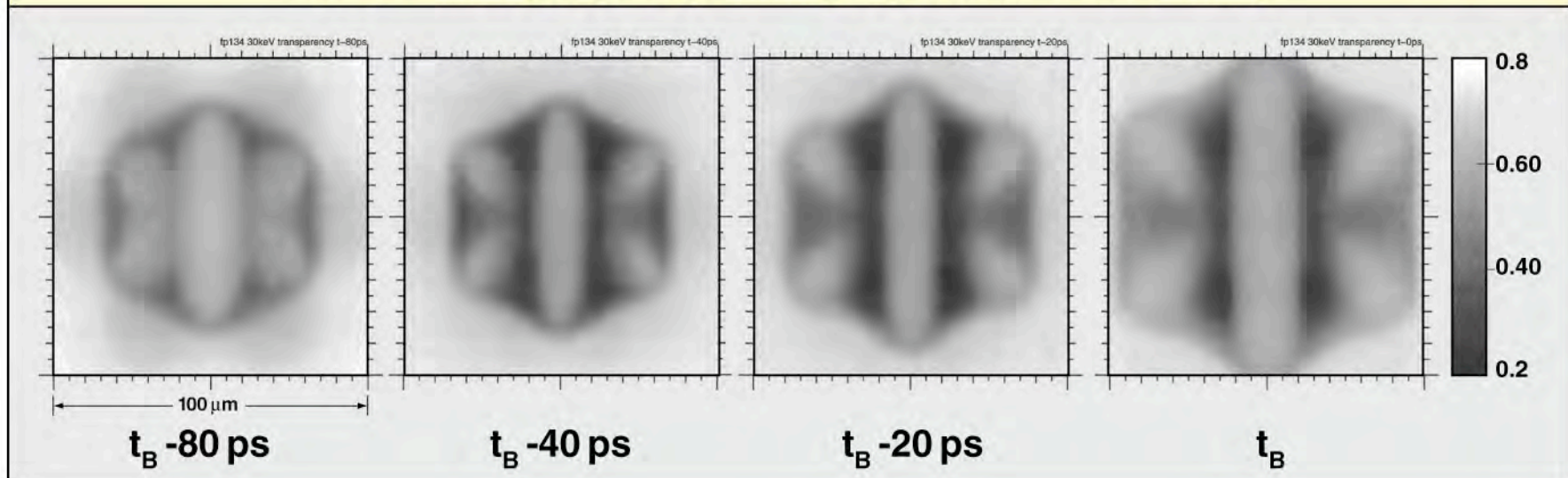
**NIC High Yield
Diagnostics
($>10^{19}$ DT neutrons)**

Magnetic Recoil Spectroscopy (MRS), T_{ion} and ρ_r , 6 m (no vulnerable components) -



Multiple ARC radiographs at intervals ~20 – 80 ps with ~10 ps exposure times would produce valuable time-history data (Phys. Rev. Lett. worthy)

ARC Radiographs (same gray scale at all times)

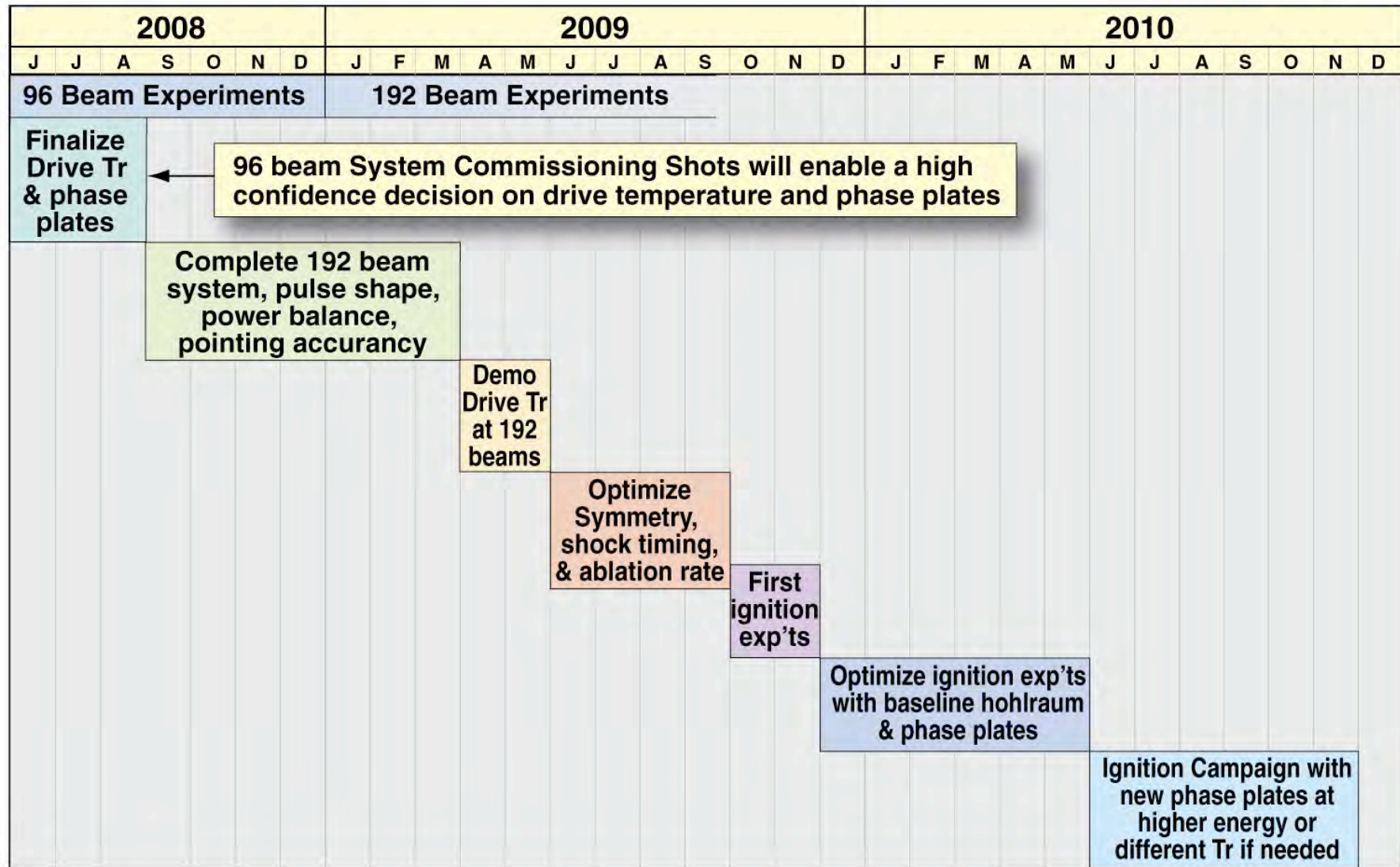


Multiple ARC images combined with reaction history and primary neutron imaging provide detailed core diagnostics

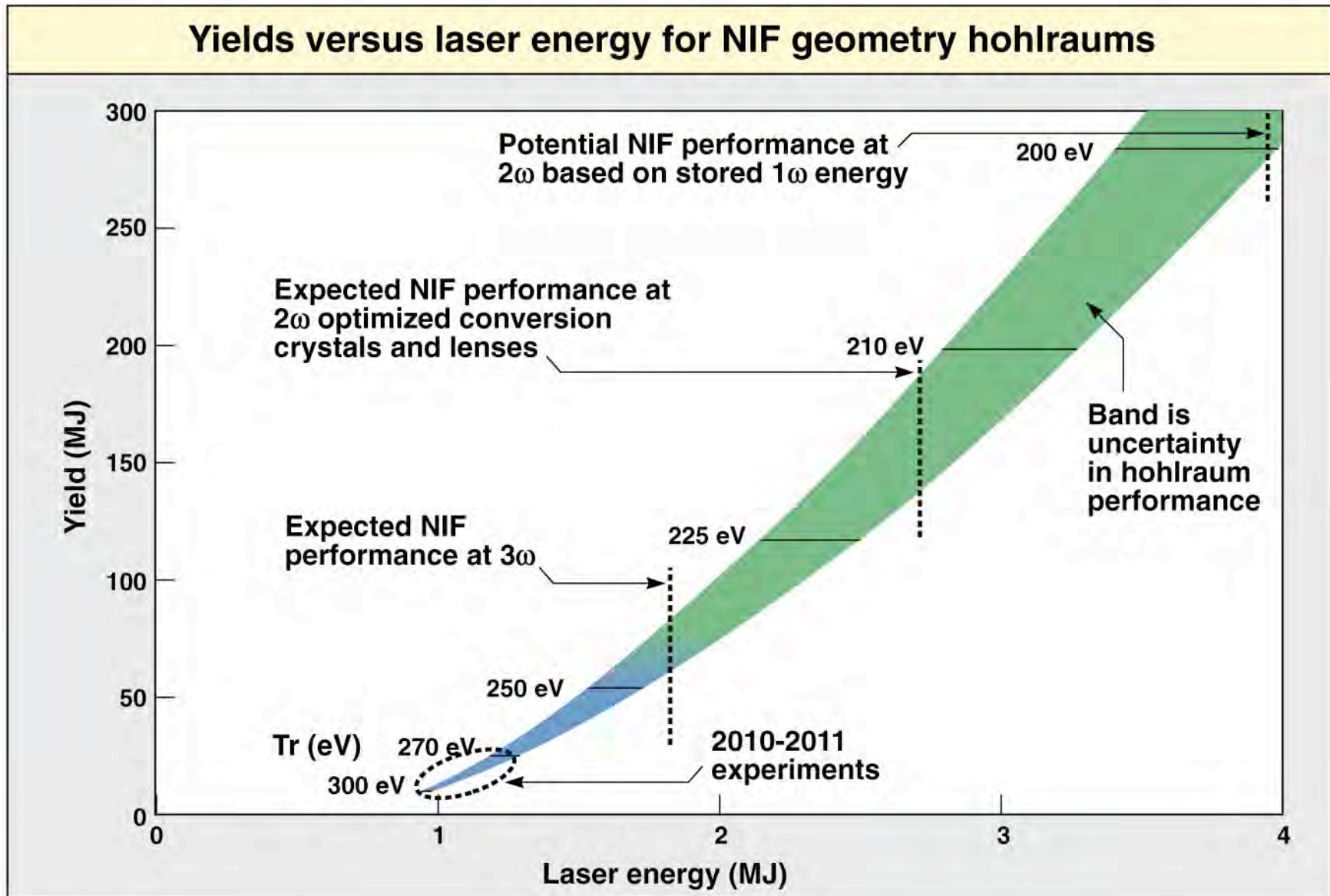
We are developing an ignition program plan during system commissioning to decrease overall risk



The National Ignition Campaign



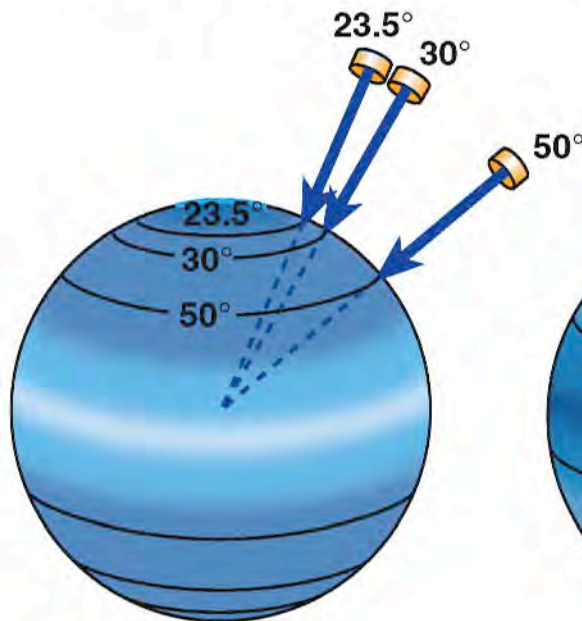
Ultimately, yields well in excess of 100 MJ may be possible on NIF



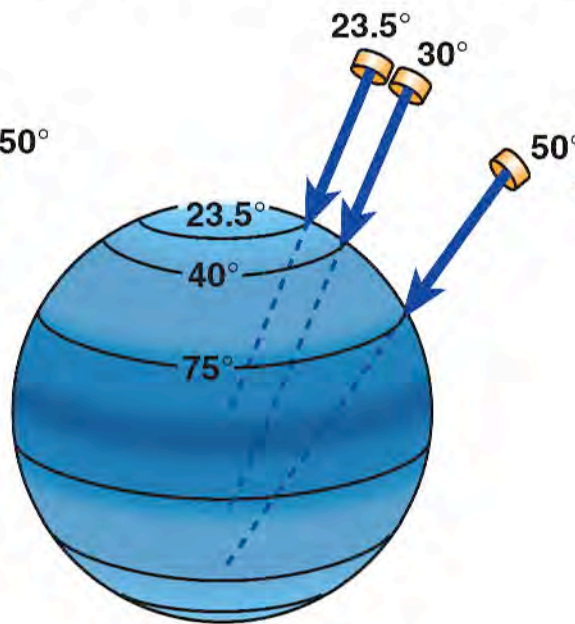
Direct drive can achieve ignition conditions while NIF is in the x-ray-drive configuration



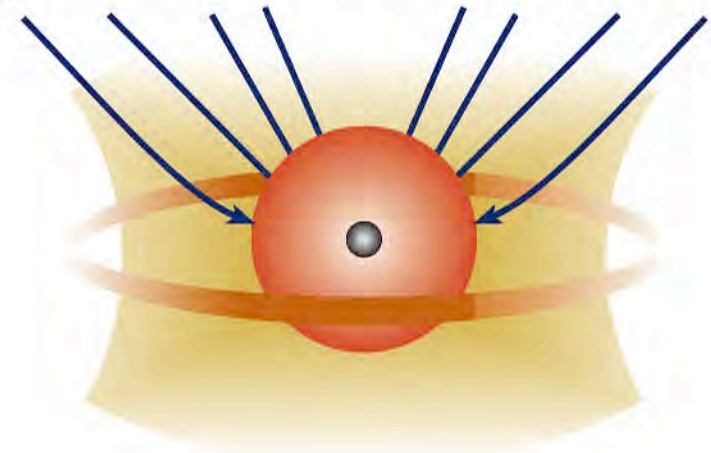
Standard pointing with x-ray-drive configuration



Repointing for polar direct drive (PDD)



Saturn concept

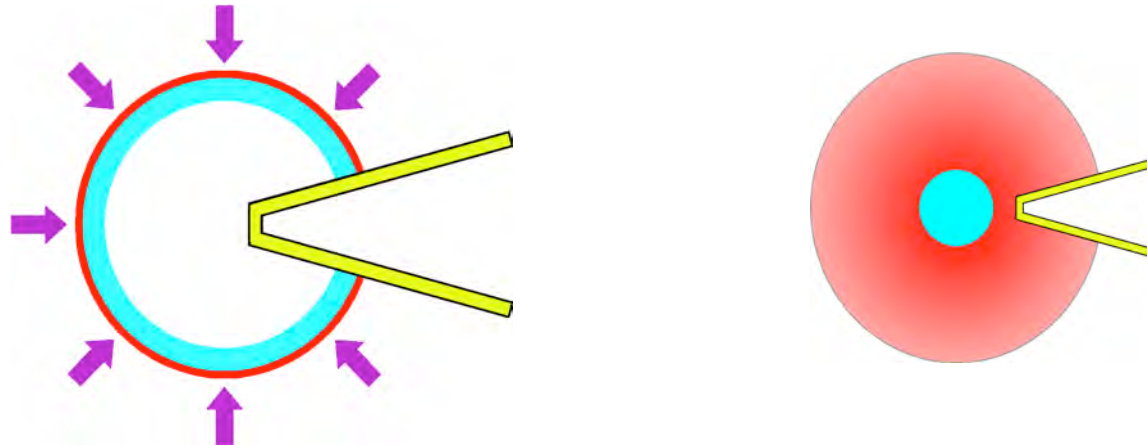


Experimental and theoretical progress gives increasing confidence in achieving PDD ignition.

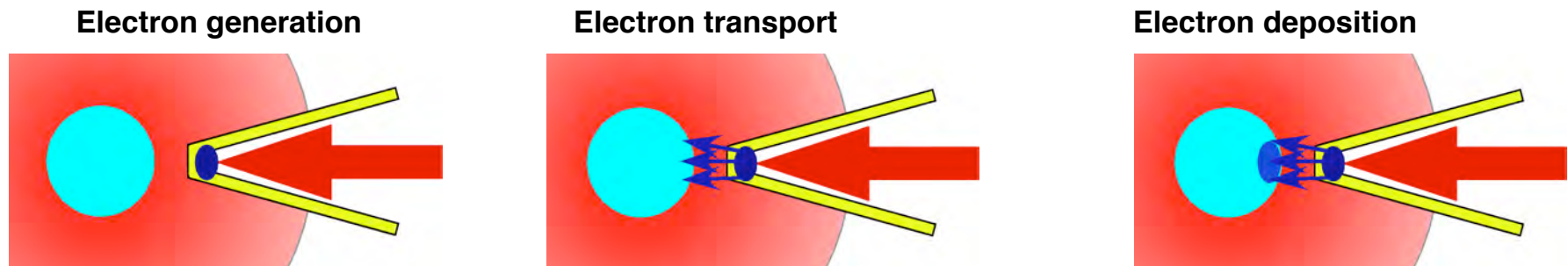
Fast ignition, which separates the fuel compression and ignition, will be tested on NIF



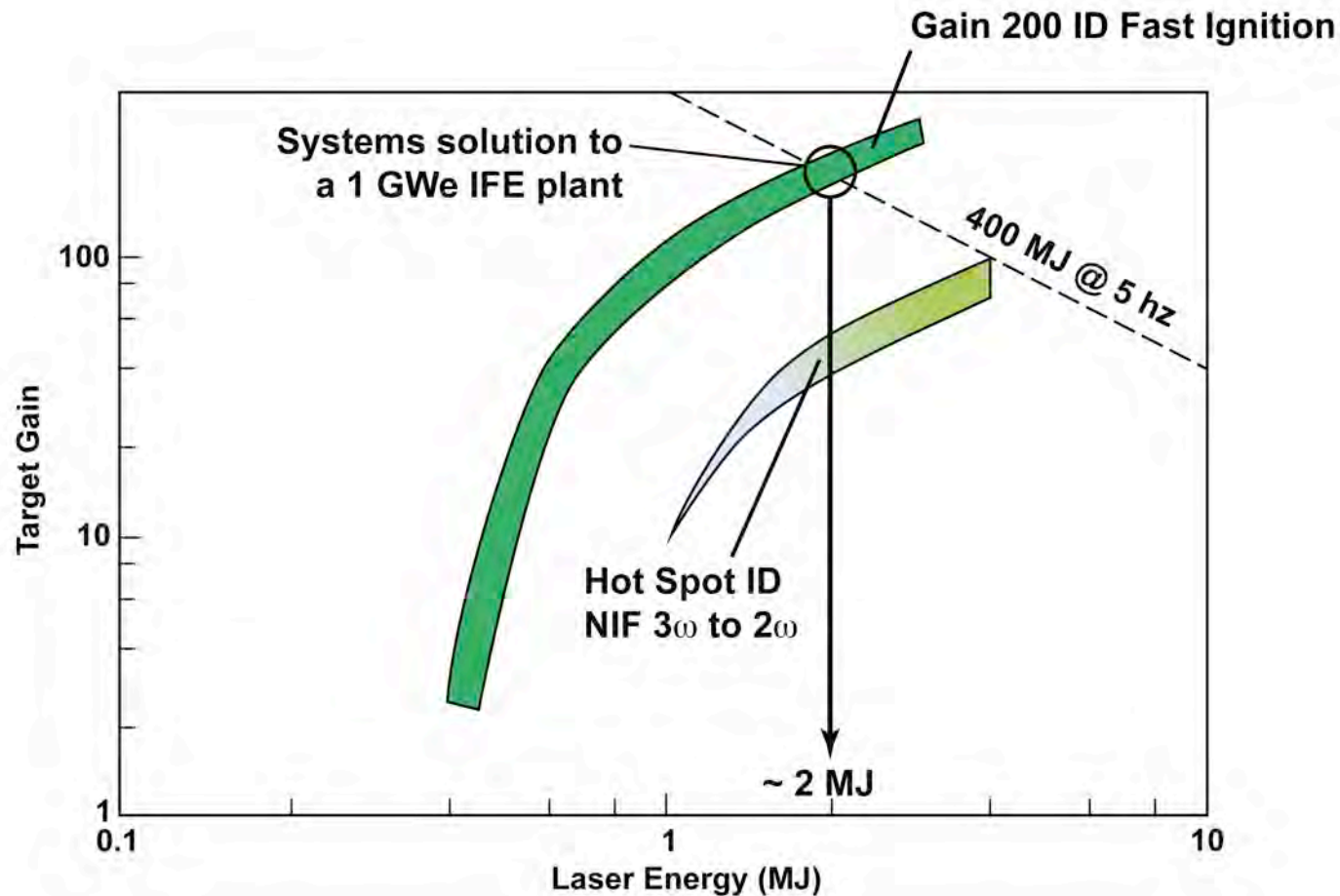
- The compression laser assembles the fuel to uniform, high density:



- The ignition laser generates hot electrons that propagate through to the dense fuel and deposit their energy initiating a burn wave:



When the requirements of low solid angle illumination is imposed, ID Fast Ignition stands out



We are also studying Direct Drive FI which may offer an advantage

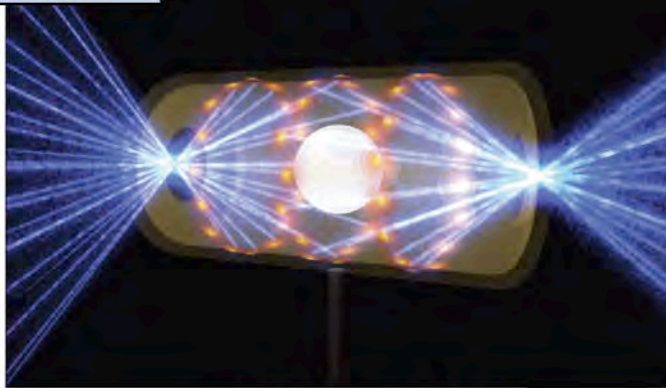
NIF Project



Completion in 2009

**NIF is a
National User
Facility**

National Ignition Campaign



2006—2012

National User Facility

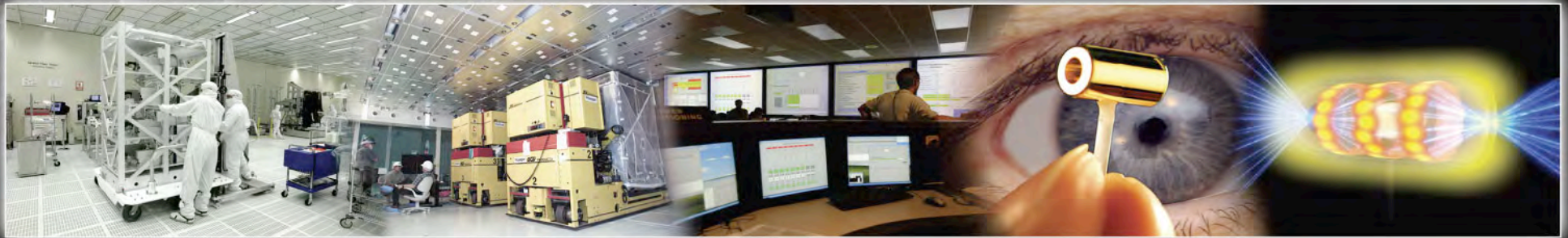


2009—2030

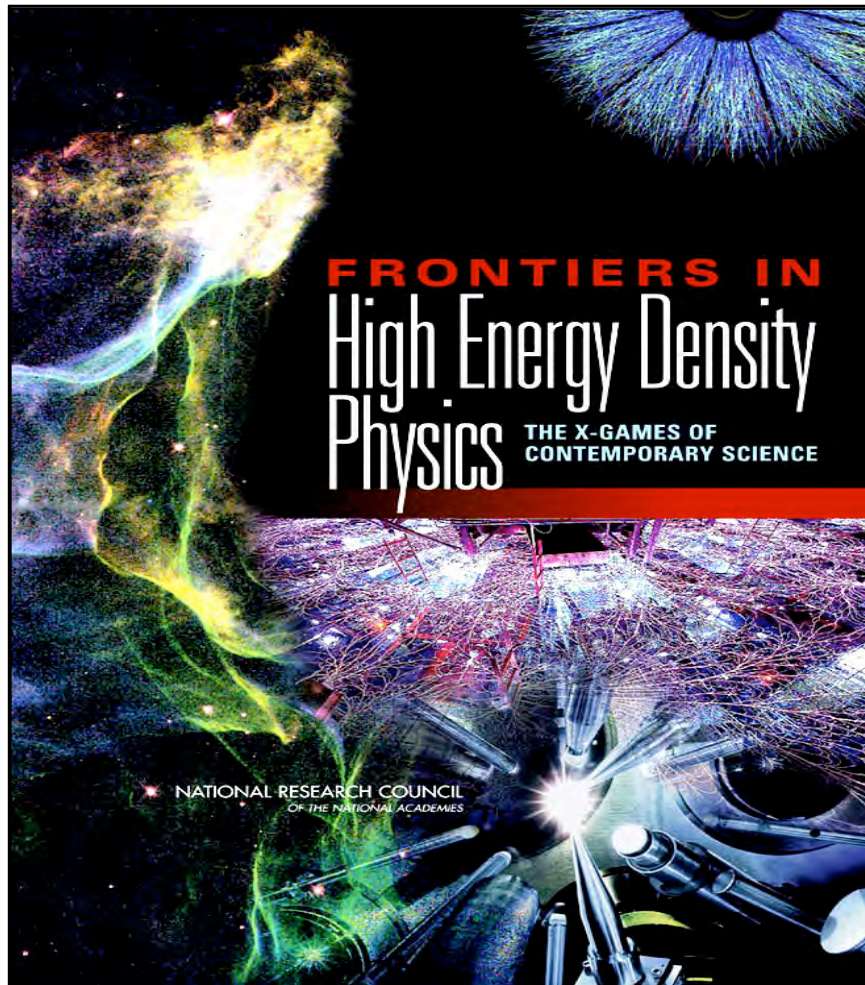
- A “Governance Model” is under development
- User friendly environment is being designed

National Ignition Facility

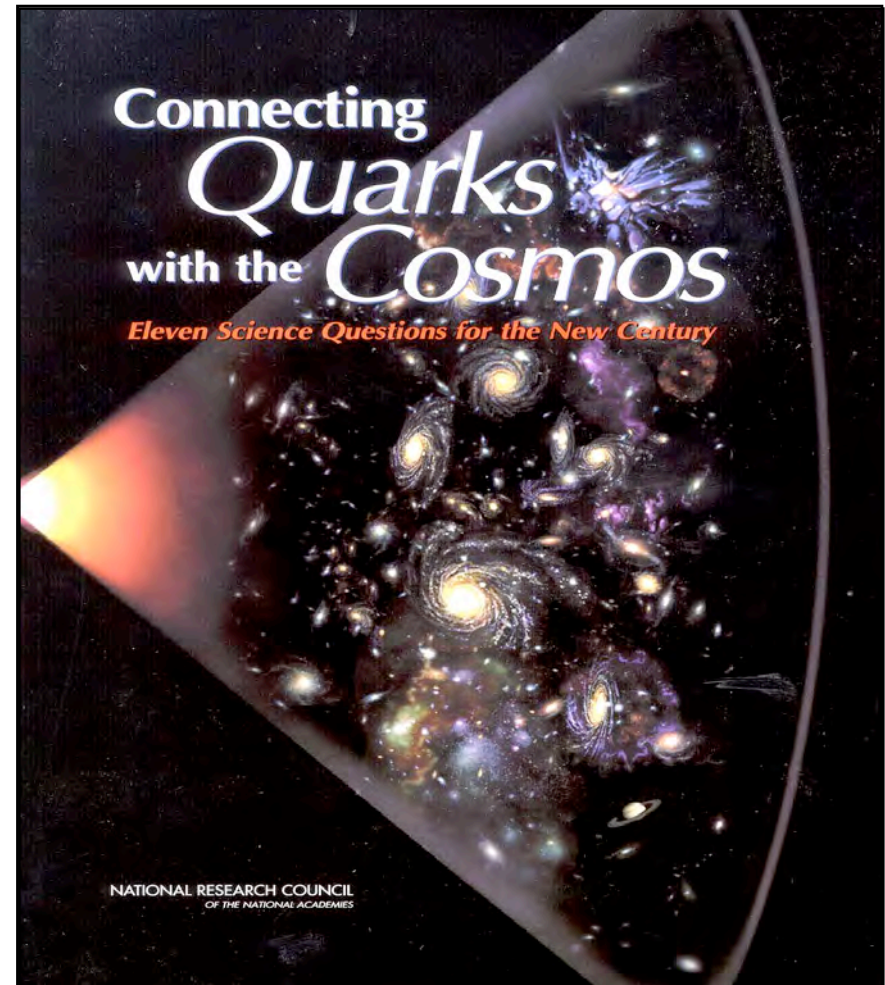
Three Years to a New Age for Science



NIF can play a key role in international science vision



**NRC committee on HEDP:
X-Games of Contemporary Science**



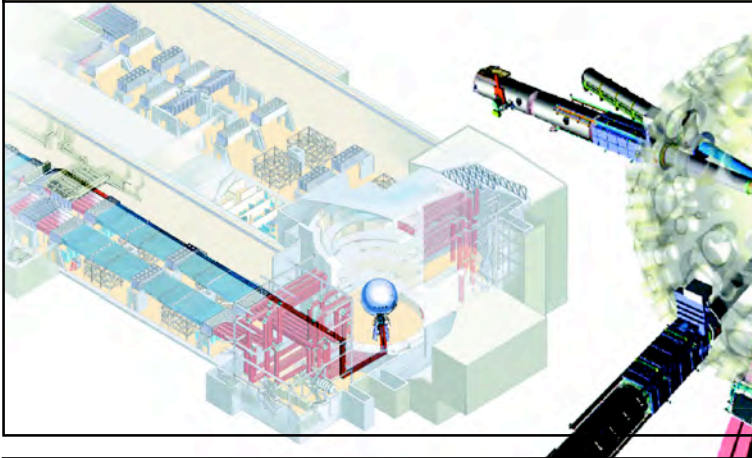
**NRC committee on the
Physics of the Universe**

NIF will access unprecedented high energy density regimes

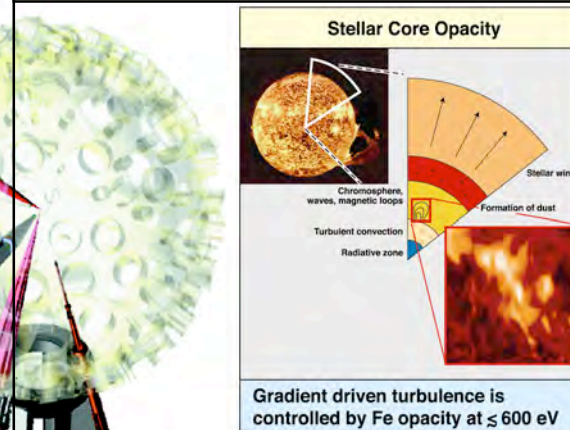


The National Ignition Facility

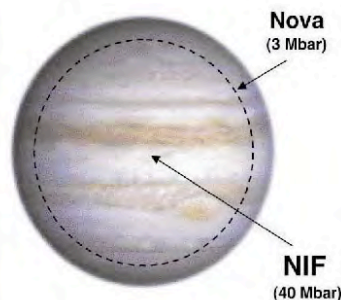
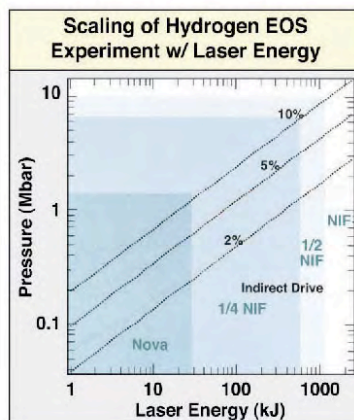
NIF Will Create a Huge Flux of Neutrons



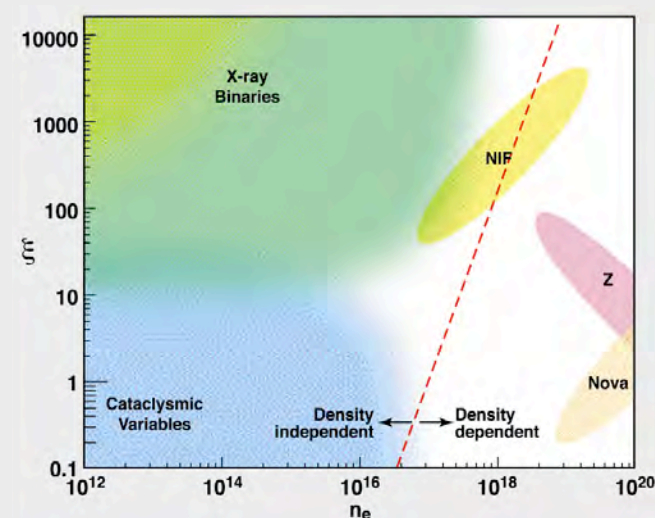
NIF Will Create Thermal Plasmas at the Conditions of Stellar Interiors



NIF Will Drive Targets to Pressures Found at the Center of Jupiter



NIF Will Produce Enough X-Ray Flux to Simulate Conditions in an Accretion Disk



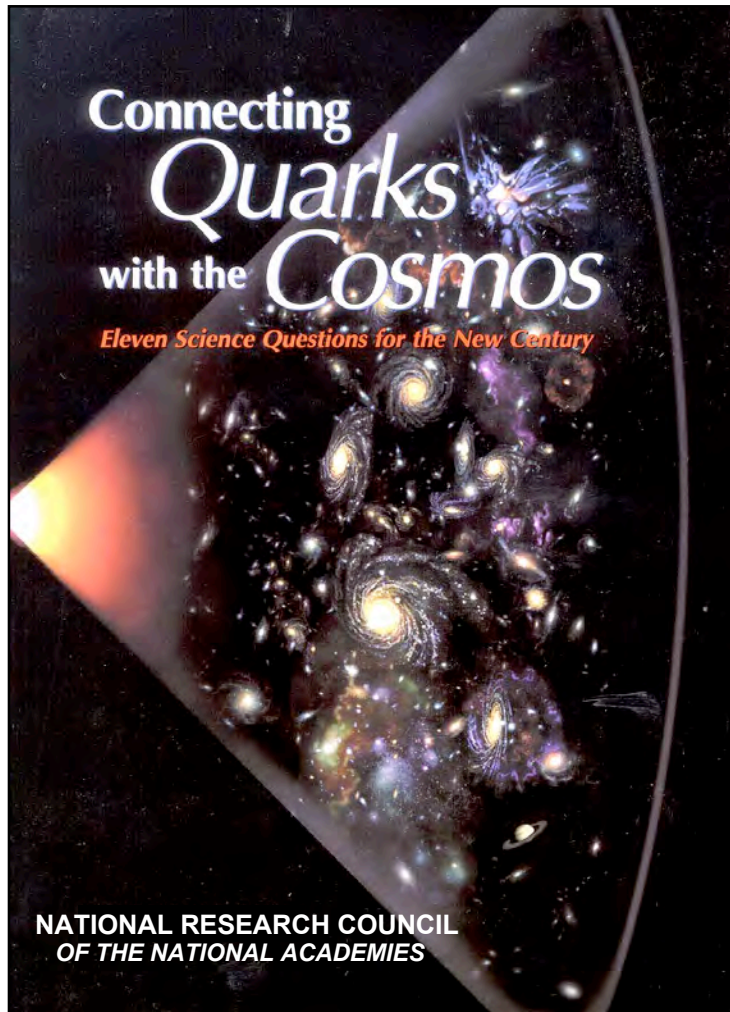
NIF's Scientific Environments

- These are the conditions of **Extreme Laboratory Astrophysics**
 - $T > 10^8$ K matter temperature
 - $\rho > 10^3$ g/cc density
 - Those are both 7x what the Sun does!
Helium burning, stage 2 in stellar evolution, occurs at 2×10^8 K!
- Core-collapse Supernovae, colliding neutron stars, operate at $\sim 10^{20}$ n's/cc
 - NIF: $\rho_n = 10^{17}$ neutrons/cc
- These apply to Type Ia Supernovae!
 - Electron Degenerate conditions
 - Rayleigh-Taylor instabilities for (continued) laboratory study.
- Only need \sim Mbar in shocked hydrogen to study the EOS in Jupiter & Saturn
 - Pressure $> 10^{11}$ bar



These certainly qualify as “unprecedented.”

The NRC committee on the Physics of the Universe highlighted the new frontier of HED science



Eleven science questions for the new century:

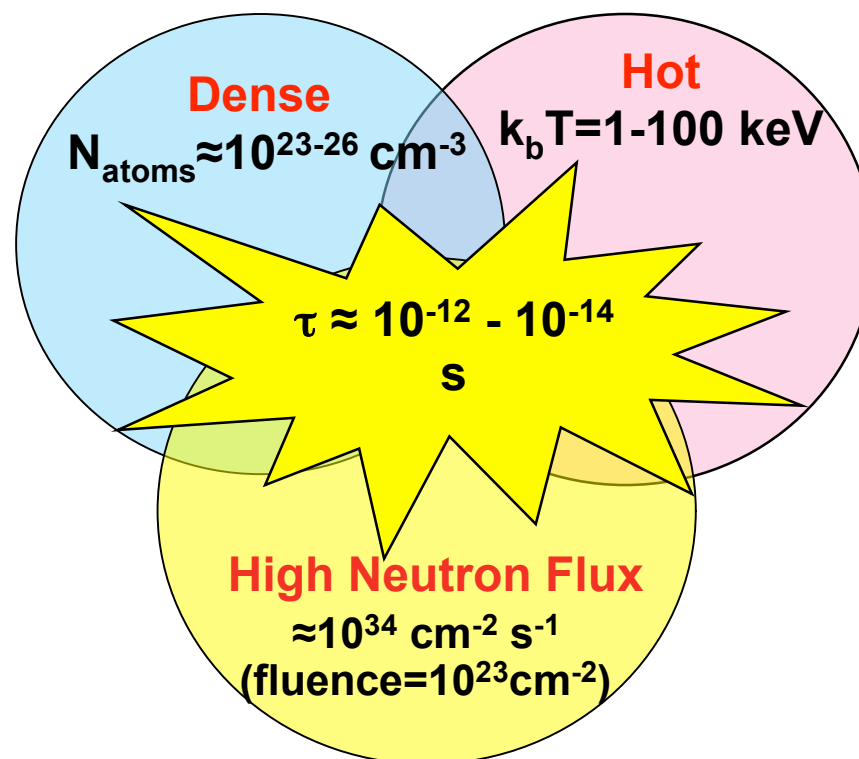
- 2. What is the nature of dark energy?**
- 4. Did Einstein have the last word on gravity?**
- 6. How do cosmic accelerators work and what are they accelerating?**
- 8. What are the new states of matter at exceedingly high density and temperature?**
- 10. How were the elements from iron to uranium made?**

Findings:

- HEDP provides crucial msmts relevant to interpreting astrophysical observations**
- The field has great promise; should be better coordinated across the Federal agencies**

Nuclear science on NIF

- Unique conditions on NIF will enable studying:
 - Dynamics of nuclei in excited states
 - Charged particle reactions relevant to nucleosynthesis
 - Solar neutrino physics



A working group has been formed including: LLNL (Schneider), LBNL (Phair), UCB (Moretto), Univ. Notre Dame (Wischer), Colorado School of Mines (Greife), GSI, University of Oslo

NIF's planning supports DOE's goals for "civilian research" and NNSA-SC partnering



Science Sept 29 Issue, p1874

NEWSFOCUS

Ray Orbach Asks Science to Serve Society

For a decade, chemist Radoslav Adzic has explored the basic structure of metal-electrolyte interfaces at Brookhaven National Laboratory in Upton, New York. His employer, the U.S. Department of Energy (DOE), has long sponsored fundamental science on catalysis in such systems in hopes of making hydrogen fuel cells efficient enough to one day replace fossil fuels as an energy source. But it wasn't until 2004 that Adzic decided to tackle a research question with more direct applications: how to use monolayers of platinum to build cheaper fuel cells, focusing on hydrogen.

It wasn't a random decision. The year before, President George W. Bush had proposed an 8-year, \$1.2 billion hydrogen fuels program that would begin with applied engineering studies. After attending a DOE-sponsored workshop to discuss the basic research needed to turn hydrogen into a commercially viable fuel, Adzic won a \$700,000 grant to study

Los Alamos National Laboratory in New Mexico.

Another barrier to developing new technologies, says Badman, is DOE's current compartmentalized bureaucracy. In July, he sent out a memo giving Orbach "detailed access" to DOE's vast empire, hoping that regular meetings among disparate programs will break through that mentality. It's not a new concept, Orbach says, but "what's new is the intensity and importance" of those meetings.

Money greases the wheels of cooperation. In addition to the hydrogen initiative and a similar effort in solar energy, Orbach has called for \$250 million for biofuel start-ups involving industrial scientists, technologists, and genomicists (*Science*, 11 August, p. 746). Sharlene Weatherwax, a DOE program manager, says a previous partnership with DOE's technology program might have consisted of a single grant.

Orbach knows that change doesn't come easily for areas, such as nuclear weapons development, that have traditionally been walled off from civilian research. In initial meetings with applied-research managers, he admits, "people don't quite know what to make of us." But Edward Moses, director of the National Ignition Facility, a superlaser at Lawrence Livermore National Laboratory in California, says Orbach is helping him grow a civilian research community to utilize an instrument designed to maintain the nation's nuclear arsenal.

Some fear that such cross-fertilizing could weaken basic science at DOE. "There is a danger of letting the basic program become a technical-



Teammates. Ray Orbach (left) hopes researchers can help his boss, Energy Secretary Samuel Bodman, (right) do his job, too.

support enterprise for the applied programs," says energy expert Robert Fri, a former Environmental Protection Agency official who believes unfettered basic work can "cook up" whole new energy ideas. Materials scientist Ward Plummer of the University of Tennessee, Knoxville, decries a 20% decline in funding core, unsolicited research within DOE's Office of Basic Energy Sciences in the last 3 years at the same time that solar energy, nanotechnology, and hydrogen programs have grown.

Plummer and others hope that DOE's new effort to define so-called grand challenges will stop that erosion. And although Orbach says he has no plans to "fuzz the boundaries" between basic and applied work, he is looking for greater cooperation between the two camps. A recent discussion with managers studying how fluids flow in dry soil at DOE's planned nuclear waste fuel repository at Yucca Mountain, Nevada, proves its value, he says. "When we met with Fossil Energy and learned more about carbon dioxide sequestration," Orbach recalls, "it suddenly popped out that that's the same problem."

Whatever happens, Orbach says DOE is determined to squeeze more impact out of its science. That's good news for Adzic, who relishes taking on challenges "directly important to society." It's also a good deal for academics. "If you publish something relevant" to a problem, says Adzic, "your paper is more [often] cited."

—ELI KINTISCH

ORBACH'S DOE

Orbach knows that change doesn't come easily for areas, such as nuclear weapons development, that have traditionally been walled off from civilian research. In initial meetings with applied-research managers, he admits, "people don't quite know what to make of us." But Edward Moses, director of the National Ignition Facility, a superlaser at Lawrence Livermore National Laboratory in California, says Orbach is helping him grow a civilian research community to utilize an instrument designed to maintain the nation's nuclear arsenal.

Keys to the kingdom. No one doubts that fundamental research could better fulfill energy needs. A 1997 report by the President's Council of Advisors on Science and Technology, for example, called for "better coordination" between basic and applied energy research. "Everyone knows it's a problem, but nothing's happened," says physicist George Crabtree, a manager at DOE's Argonne National Laboratory in Illinois.

One obstacle is the current rewards system in academia. Take the science behind superconductivity, which holds the promise of low-resistance power lines or incredibly efficient transformers. The kind of discovery that earns a scientist a paper in a top journal—learning why a material changes phase at a certain temperature—is too theoretical to help a company trying to make superconducting materials. But a commercially valuable yet incremental improvement in that technology wouldn't interest those top-tier journals. So a scientist might not even bother to record such an advance. "If the currency is just PRL [*Physics Review Letters*], *Nature*, and *Science*, you'll just move on," says materials scientist John Sarrao of

1874

29 SEPTEMBER 2006 VOL 313 SCIENCE www.sciencemag.org
Published by AAAS

"External Users" participated in the 2004 NIF Early Light Experiments

Physical Review Letters

vol. ending
MARCH 2005

Experimental Investigation of High-Mach-Number 3D Hydrodynamic Jets at the National Ignition Facility

B. E. Blue,¹ S. V. Weber,¹ S. G. Glendinning,¹ N. E. Lanier,² D. T. Woods,¹ M. J. Bono,¹ S. N. Dixit,¹ C. A. Hayna,¹ J. P. Holder,¹ D. H. Kalantar,¹ B. J. MacGowan,¹ A. J. Nikitin,¹ V. V. Rekow,¹ B. M. Van Wenterghem,¹ E. I. Moses,¹ P. E. Stry,¹ B. H. Wilde,² W. W. Hsing,¹ and H. F. Robey¹

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The first hydrodynamic experiments were performed on the National Ignition Facility. A supersonic jet was formed via the interaction of a laser-driven shock (~40 Mbar) with 2D and 3D density perturbations. The temporal evolution of the jet's spatial scales and ejected mass were measured with point-projection x-ray radiography. Measurements of the large-scale features and mass are in good agreement with 2D and 3D numerical simulations. These experiments provide quantitative data on the evolution of 3D supersonic jets and provide insight into their 3D behavior.

DOI: 10.1103/PhysRevLett.94.095005

PACS numbers: 52.35.Tc, 52.50.Jn, 52.57.-a

The interaction of a shock wave with a density perturbation is a problem of basic scientific interest [1] with specific application to astrophysics [2] and inertial confinement fusion (ICF) [3]. For instance, high-Mach number hydrodynamic jets, which can result from a shock-perturbation interaction, are ubiquitous features of supernovae in astrophysics [4–7] and may result from the presence of capsule joints or cryogenic fuel tubes in ICF [8]. Although the spatial scales of these systems vary over 16 orders of magnitude from supernovae jets (~10¹⁰) to micron scale jets inside ICF capsules, they are unified by the physics of a high-Mach number shock interacting with a perturbation at a two fluid interface. In both systems the shock-perturbation interaction results in a jet of plasma being ejected ahead of the shocked material interface. In the case of supernovae, a jet provides a possible mechanism for explaining the observation of the early appearance of core high Z elements (nickel, iron, etc) [9] in the outer helium and hydrogen envelope. In the case of ICF capsules, fabrication joints or fill tubes can mix cooler shell material into the fuel before optimal compression, possibly affecting ignition [8]. Previous work has studied the spatial evolution of 2D jets [6]. This Letter describes quantitative measurement of the evolution of 3D supersonic jets and provides insight into their 3D behavior. To validate the simulations of these phenomena, there are several parameters of critical importance. They are the spatial dimensions, the characteristic velocities, the total mass of material and the spatial mass distribution of the jet material.

An experiment was conducted to investigate jet formation in 2D and 3D shocked systems using the first four (four beams) of the National Ignition Facility (NIF) [11] located at Lawrence Livermore National Laboratory. A 1.5 ns, 6 kJ (2 × 3 kJ beams), 350 (351 nm wavelength), 1000 μm diameter laser pulse (4 × 10¹⁴ W/cm²) was used to drive a 40 Mbar shock wave into aluminum targets

backed by 100 mg/cc carbon aerogel foam. The experimental package consisted of a 101 ± 2 μm thickness aluminum disk placed in direct contact with a shock tube, 162 ± 2 μm diameter hole. The hole was drilled either 0° for the case of a two-dimensional cylindrical symmetric target [Fig. 1(a)] or 45° for the case of a three-dimensional target [Fig. 1(b)]. The two 800 diameter aluminum disks were inserted into a 2000 diameter, 250 μm thick gold washer that delays propagation of shocks around the exterior of the package. The front surface of the target was coated a 57 ± 2 μm thick polystyrene ablator. The carbon was encased in a polystyrene shock tube with a thickness of 40 μm.

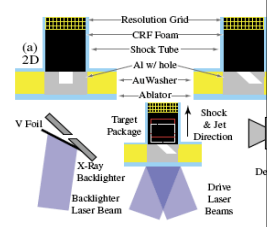


FIG. 1 (color). Schematic of a 2D target (a), a 3D target (b), and the radiographic configuration used on NIF (c) (not to scale).

0031-9007/05/94(9)/095005(4)\$23.00

095005-1

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Nuclear Fusion

INSTITUTE OF PHYSICS PUBLISHING
Nuclear Fusion 44 (2004) S185–S190
PII: S0029-5515(04)00276-8

Progress in long scale length laser-plasma interactions

S.H. Glenzer, P. Arnold, G. Bardsley, R.L. Berger, G. Bonanno, T. Borger, D.E. Bower, M. Bowers, R. Bryant, S. Buckman, S.C. Burkhardt, K. Campbell, M.P. Christ, B.L. Cohen, C. Constantin, F. Cooper, J. Cox, E. Dewald, L. Divol, S. Dixit, J. Duncan, D. Eder, J. Edwards, G. Erbert, B. Felker, J. Fomes, G. Frieders, D.H. Froula, S.D. Gardner, C. Gates, M. Gonzalez, S. Grace, G. Gregori, A. Greenwood, R. Griffith, T. Hall, B.A. Hammel, C. Haynam, G. Heestand, M. Hennesian, G. Hermes, D. Hinkel, J. Holder, E. Holdner, G. Holmeier, W. Hsing, S. Huber, T. James, S. Johnson, O.S. Jones, D. Kalantar, J.H. Kamperschroer, R. Kaufman, T. Kelleher, J. Knight, R.K. Kirkwood, W.L. Krue, W. Labiak, O.L. Landen, A.B. Langdon, S. Langer, D. Latray, A. Lee, E.D. Lee, D. Lund, B. MacGowan, S. Marshall, J. McBride, T. McCarville, L. McGrew, A.J. Mackinnon, S. Mahavadi, K. Manes, C. Marshall, J. Menapace, E. Mertens, M. Mezan, G. Miller, S. Montelongo, J.D. Moody, E. Moses, D. Munro, J. Murray, J. Neumann, M. Newton, E. Ng, C. Niemann, A. Nikitin, P. Opsahl, E. Padilla, T. Parham, G. Parrish, C. Petty, M. Polk, C. Powell, L. Reinbachs, V. Rekow, R. Rimmer, B. Rordian, M. Rhodes, V. Roberts, H. Robey, G. Ross, S. Sailors, R. Saunders, M. Schmitt, M.B. Schneider, S. Shiromizu, M. Spaeth, A. Stephens, B. Still, L.L. Suter, G. Tietbold, M. Tobin, J. Tuck, B.M. Van Wenterghem, R. Vidal, D. Voloshin, R. Wallace, P. Wegner, P. Whitman, E.A. Williams, K. Williams, K. Winward, K. Work, B. Young, P.E. Young, P. Zapata, R.E. Bahr¹, W. Seka¹, J. Fernandez², D. Montgomery² and H. Rose²

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Abstract

The first experiments on the National Ignition Facility (NIF) have employed the first four beams to measure propagation and laser backscattering losses in long scale length laser-plasma interactions. Gas-filled targets between 2 and 7 mm length have been heated from one side by overlapping the focal spots of the four beams from one quad operated at 351 nm (350) with a total intensity of 2×10^{15} W/cm². The targets were filled with 1 atm of CO₂ producing up to 7 mm long homogeneously heated plasma with densities of $n_e = 6 \times 10^{20}$ cm⁻³ and temperatures of $T_e = 2$ keV. The high energy in an NIF quad of beams with 6 kJ, illuminating the target from one direction, creates unique conditions for the study of laser-plasma interactions through the large-scale plasma was measured with a gated x-ray imager that was filtered for 3.5 keV x-rays. These data indicate that the beams interact with the full length of this ignition-scale plasma during the last ~1 ns of the experiment. During that time, the full aperture measurements of the stimulated Brillouin scattering and stimulated Raman scattering show scattering into the four quadrants at the smallest length (~2 mm), increasing to 10–12% for ~7 mm. These results demonstrate the NIF experimental capabilities and further provide a benchmark for three-dimensional modelling of the laser-plasma interactions at ignition-scale length.

PACS numbers: 52.38.-r, 52.25.-b, 52.35.-g

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S185

Physics of Plasmas

PHYSICS OF PLASMAS 13, 032703 (2006)

Hard x-ray and hot electron environment in vacuum hohlraums at the National Ignition Facility

J. W. McDonald, L. J. Suter, O. L. Landen, J. M. Foster,¹ J. R. Celeste, J. P. Holder, E. L. Dewald, M. B. Schneider, D. E. Hinkel, R. L. Kaufman, L. J. Atherton, R. E. Bonanno, S. N. Dixit, D. C. Eder, C. A. Haynam, D. H. Kalantar, A. E. Koenigs, F. D. Lee, B. J. MacGowan, K. R. Manes, D. H. Munro, J. R. Murray, M. J. Shaw, R. M. Stevenson,² T. G. Parham, B. M. Van Wenterghem, R. J. Wallace, P. J. Wegner, P. K. Whitman, B. K. Young, B. A. Hammel, and E. I. Moses

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(Received 25 October 2005; accepted 23 February 2006; published online 31 March 2006)

Time resolved hard x-ray images ($h\nu > 9$ keV) and time integrated hard x-ray spectra ($h\nu = 18–150$ keV) from vacuum hohlraums irradiated with four 351 nm wavelength National Ignition Facility [J. A. Paisner, E. M. Campbell, and W. J. Hogan, *Fusion Technol.* 26, 755 (1994)] laser beams are presented as a function of hohlraum size, laser power, and duration. The hard x-ray images and spectra provide insight into the time evolution of the hohlraum plasma filling and the production of hot electrons. The fraction of laser energy detected as hot electrons (F_{hot}) shows a correlation with laser intensity and with an empirical hohlraum plasma filling model. In addition, the significance of Au K-alpha emission and Au K-shell reabsorption observed in some of the bremsstrahlung dominated spectra is discussed. © 2006 American Institute of Physics.
[DOI: 10.1063/1.2186927]

I. INTRODUCTION

High-Z cavities or hohlraums are an essential part of the indirect drive approach to internal confinement fusion (ICF).¹ These hohlraums convert intense laser light into soft x rays that can symmetrically implode fuel capsules or can be used for a wide variety of other high-energy density experiments. The physics of laser absorption in the hohlraum must be understood in order to predict the hohlraum symmetry, radiation temperatures achievable within the hohlraums, and the efficiency of coupling of the driver energy to the capsule. Several studies of the interaction of lasers with cavities and their associated plasmas have been conducted over the past decades.^{2–5} Parametric instability growth leading to reflection of laser light by the plasma⁶ can present a limit to the achievable radiation temperature in laser-heated hohlraums.⁷ However, in this paper we focus on the effect of hohlraum plasma filling on hot electron production that results from the laser-hohlraum plasma interactions as evidenced by hard x-ray photos.

Single-ended cylindrical hohlraums ("halfraum") were used in this study, as illustrated with a computer-generated image in Fig. 1(a). The laser beams enter the halfraum along its axis through a laser entrance hole (LEH) (bottom), striking the back wall (top), rapidly heating the Au producing laser ablated plasma and x rays. The x rays in turn interact with and heat the unilluminated walls, producing x-ray ablated plasma and reemitted x rays. In contrast to laser-disk experiments,⁸ where the ablated plasma is free to expand, the hohlraum confines and accumulates the plasma.⁹ As the plasma moves into the path of the incident laser beam, hot electrons (>10 keV) are produced by laser plasma instabil-

ties such as the stimulated Raman instability.¹⁰ Quantifying the hot electron production is important for ignition experiments because the hot electrons can penetrate the fuel capsule, preheating the fuel and thereby making it harder to compress. Hot electrons can be important for other experiments, for example, by preheating hydrodynamic packages or by driving the plasma out of equilibrium. Hard x-ray electron bremsstrahlung emission is produced when the fast electrons interact with the surrounding plasma or the cold dense matter. Bremsstrahlung production is on the order of a few percent of the fast electron energy for high-Z materials such as Au and is proportional to Z. For very hot plasmas, hard x rays can be produced by the thermal electron distribution through bremsstrahlung or by free-bound transitions. In previous laser-plasma experiments in indirect drive targets, the hard x-ray levels have been correlated with Raman scattered laser light signals.¹¹ Often the spectrum had a harder, super-hot component thought to be produced by forward Raman scattering.¹¹

This paper describes measurements of hot electrons produced in laser heated cavities. The scaling with hohlraum size and laser power and duration are presented. The fraction of laser energy detected as hot electrons (F_{hot}) shows a correlation with laser intensity and with an empirical hohlraum plasma filling model. In addition, evidence of Au K-alpha emission and Au K-shell reabsorption in some of the bremsstrahlung dominated spectra is discussed.

II. EXPERIMENTAL SETUP

The National Ignition Facility (NIF), currently under construction,¹² is a 192-beam laser system that is designed to deliver up to 9.4 kJ (3 TW) of laser energy (power) per beam at 351 nm wavelength. The laser system will be used

¹Atomic Weapons Establishment, Aldermaston, United Kingdom.

1070-664X/06/13032703/\$23.00

13, 032703-1

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Los Alamos National Lab

University of Rochester, LLE

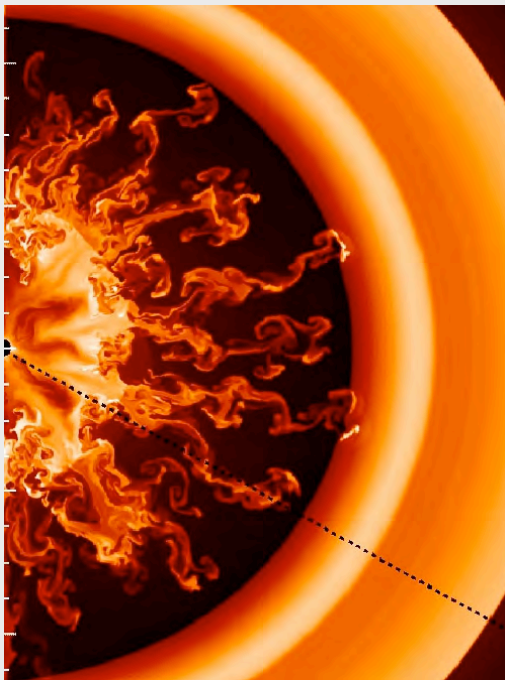
Atomic Weapons Establishment

Three university teams are starting to prepare for NIF shots in unique regimes of HED physics



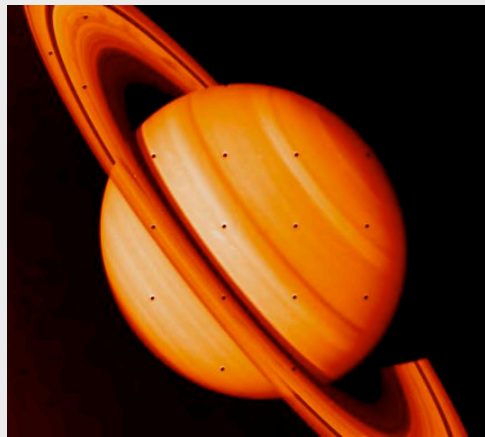
The National Ignition Facility

Astrophysics - hydrodynamics



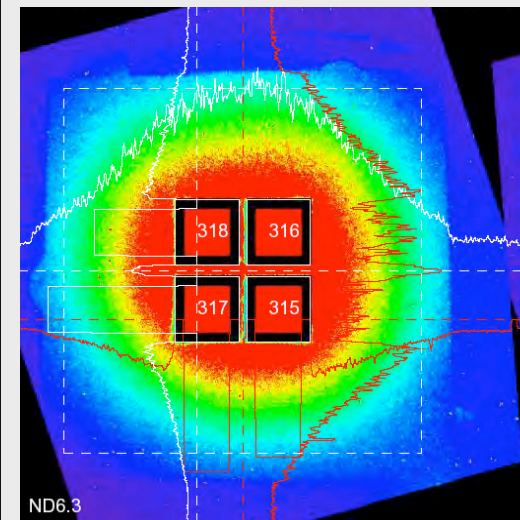
Paul Drake, PI, U. of Mich.
David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Todd Ditmire, U. Texas-Austin
LLNL hydrodynamics team

Planetary physics – EOS



Raymond Jeanloz, PI,
UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, U. Pierre & Marie
Curie, and CEA
LLNL EOS team

Nonlinear optical physics – LPI



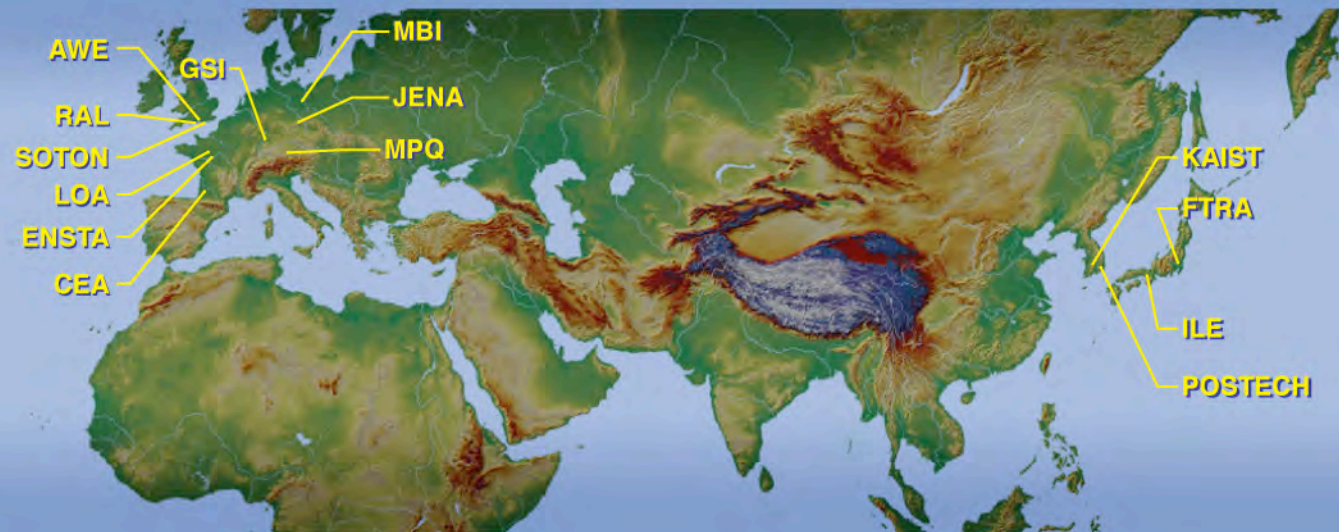
Christoph Niemann, PI,
UCLA NIF Professor
Chan Joshi, UCLA
Warren Mori, UCLA
Bedros Afeyan, Polymath
David Montgomery, LANL
Andrew Schmitt, NRL
LLNL LPI team

U.S. Academic Alliance

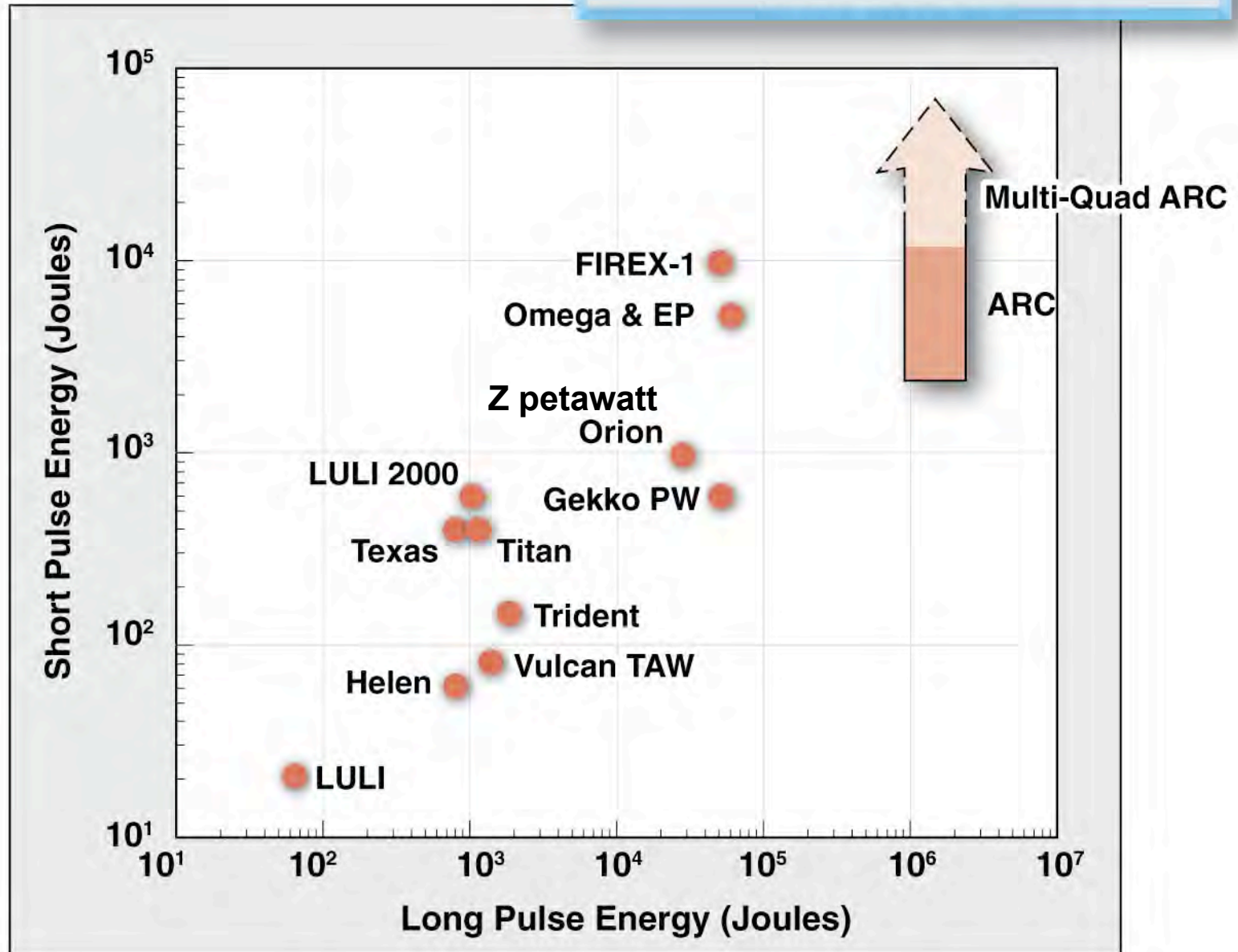


“The NIF will be a unique center of R&D that will assure the U.S. will achieve goals of SSP and HEDP not possible with any other facility”

Partnering with the International Community



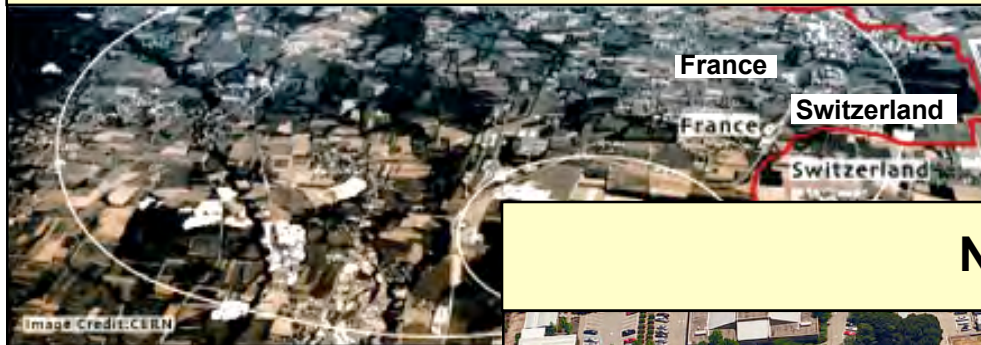
**NIF will be an integral member of
the HED community**



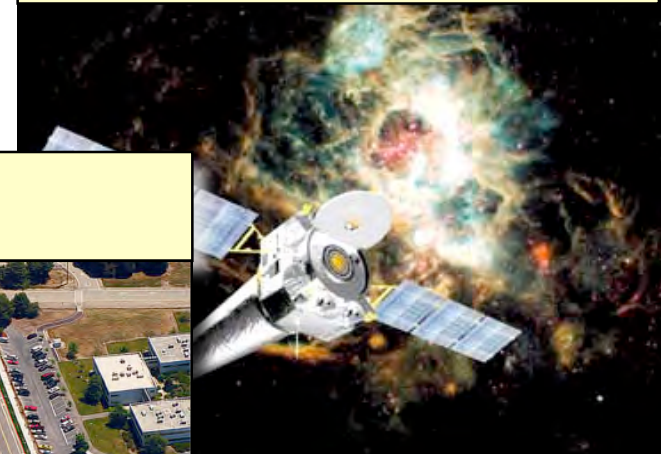
Our goal: turn NIF into the premier international center for HED experimental science



CERN



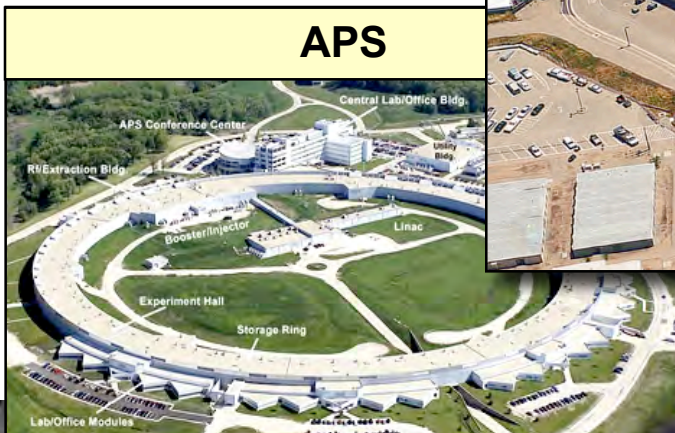
Chandra X-ray Observatory



NIF



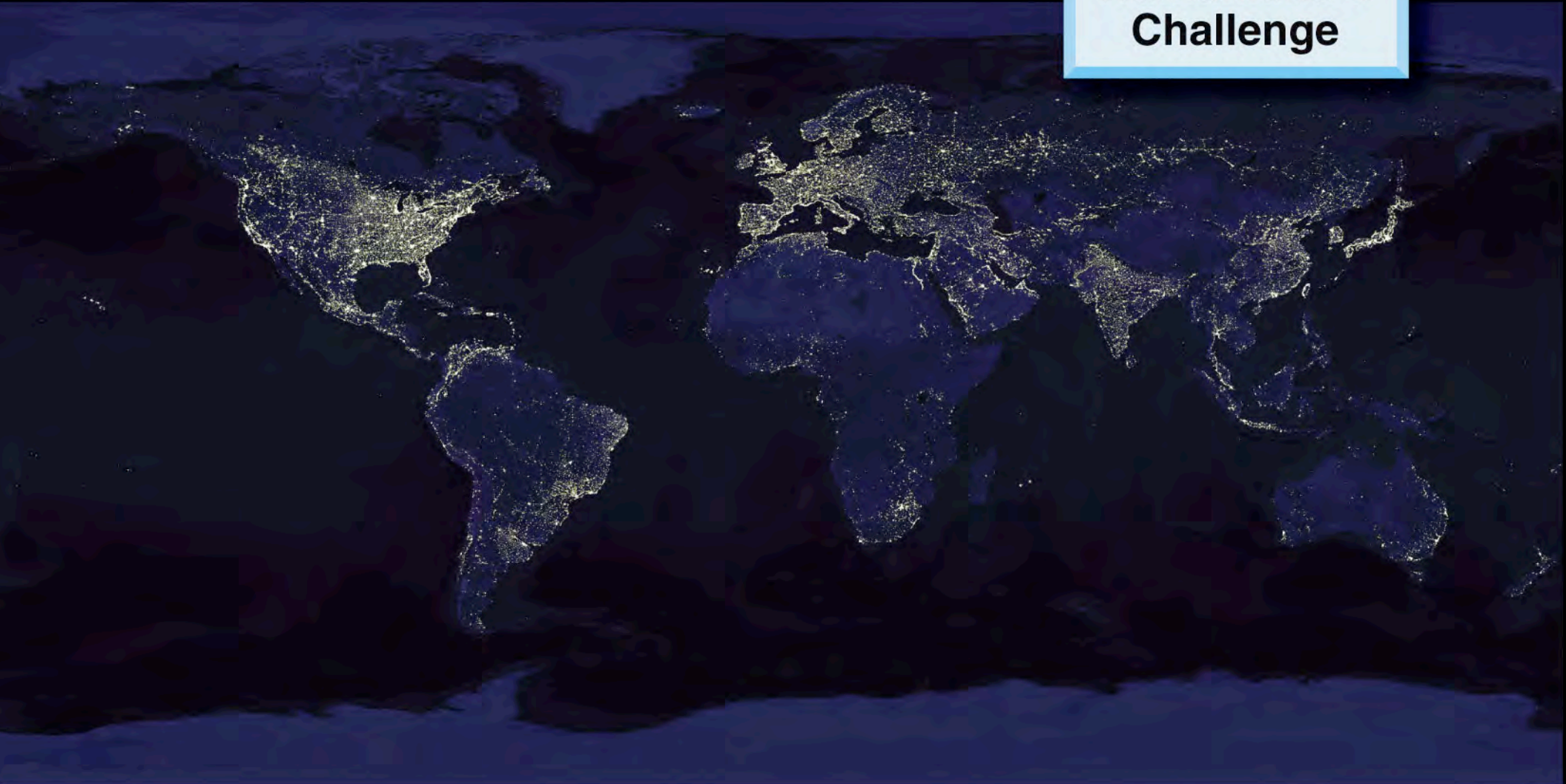
APS



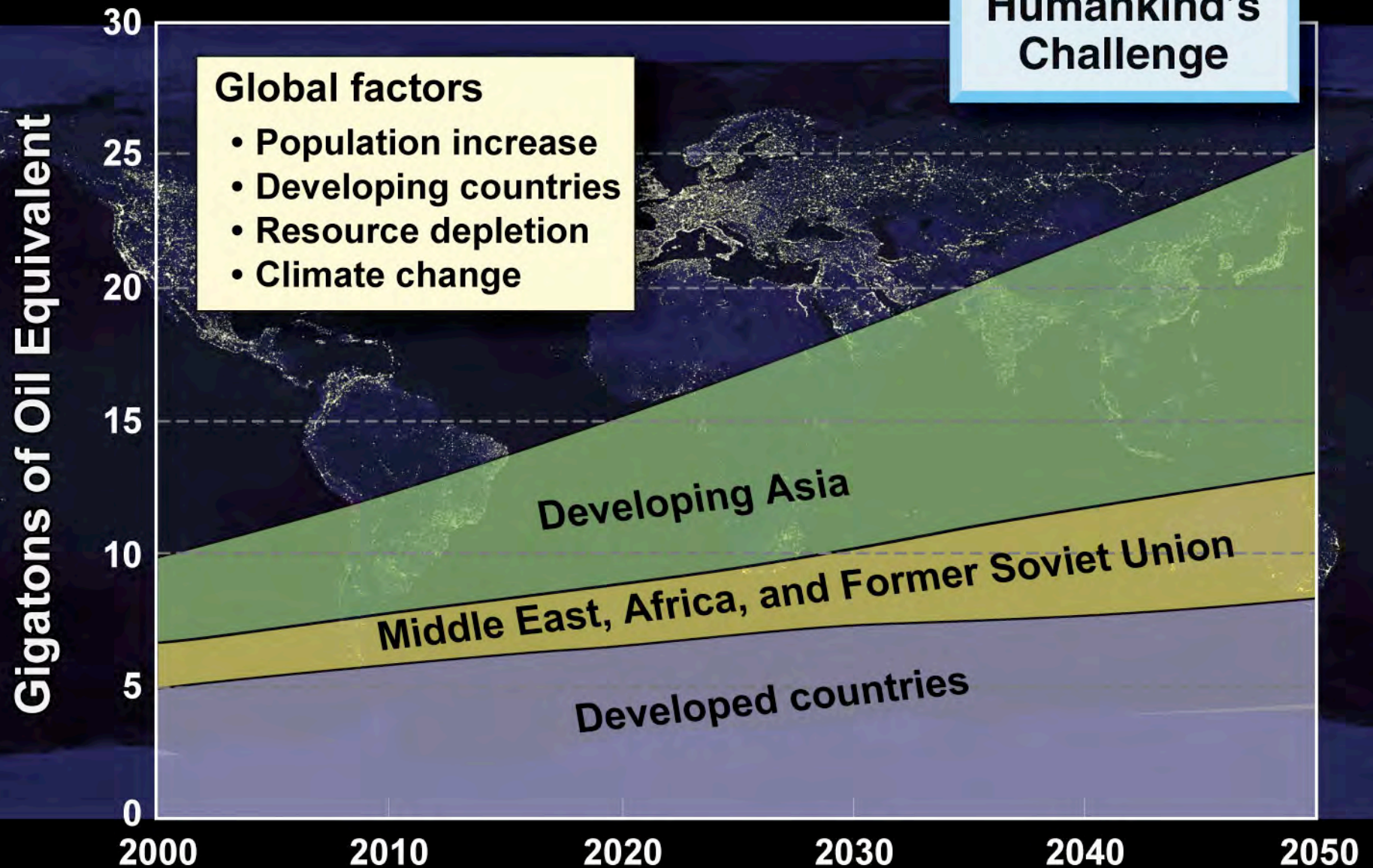
SLAC



Clean Energy: Humankind's Challenge

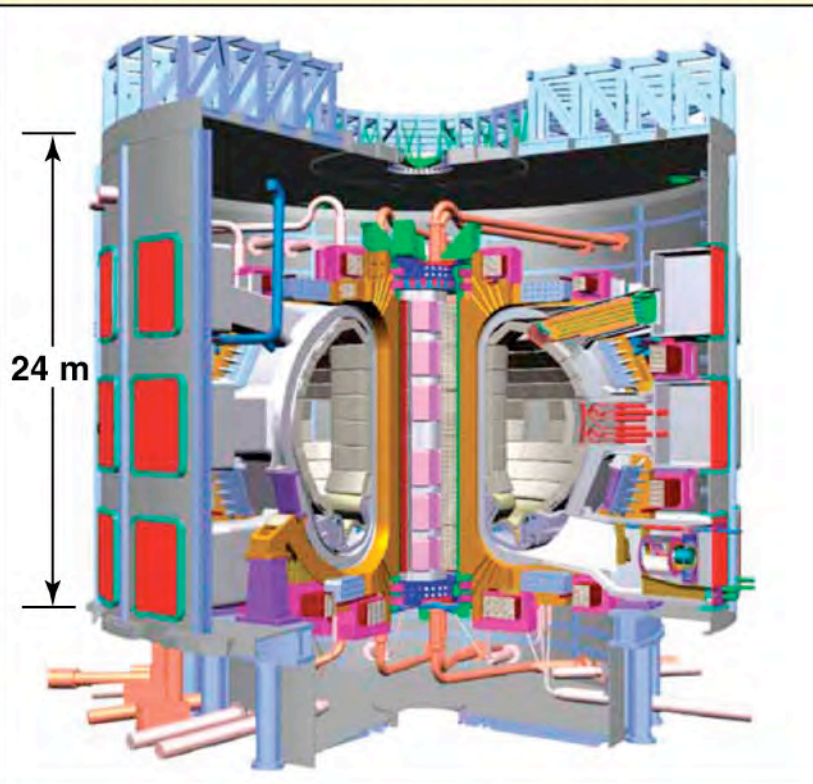


Clean Energy: Humankind's Challenge



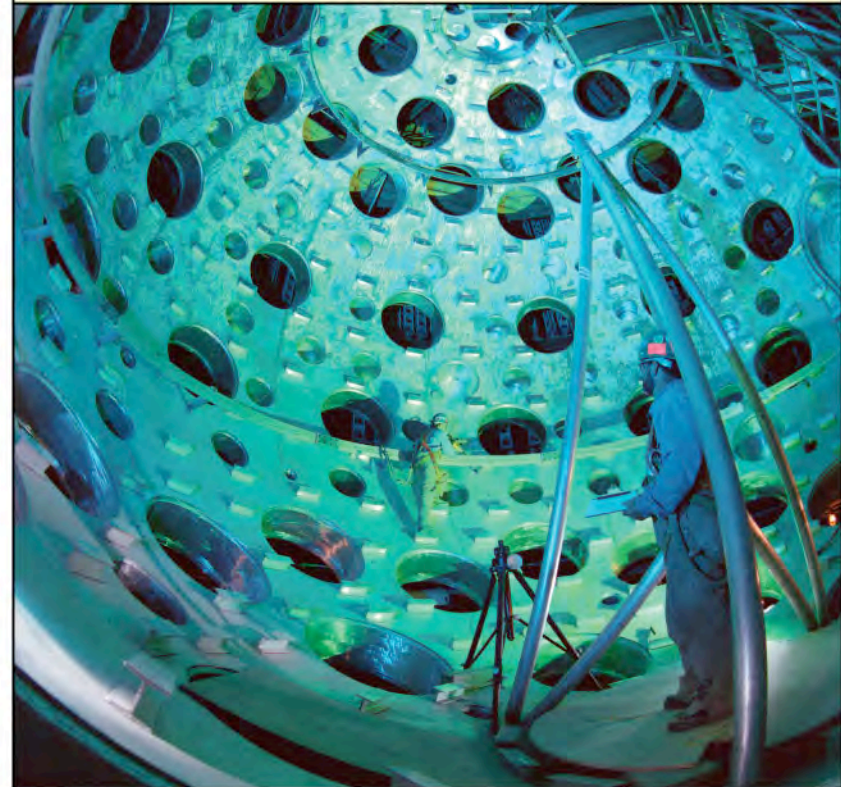
There are two major possibilities for fusion energy

Magnetic Fusion Energy (1951)



DOE Office of Science

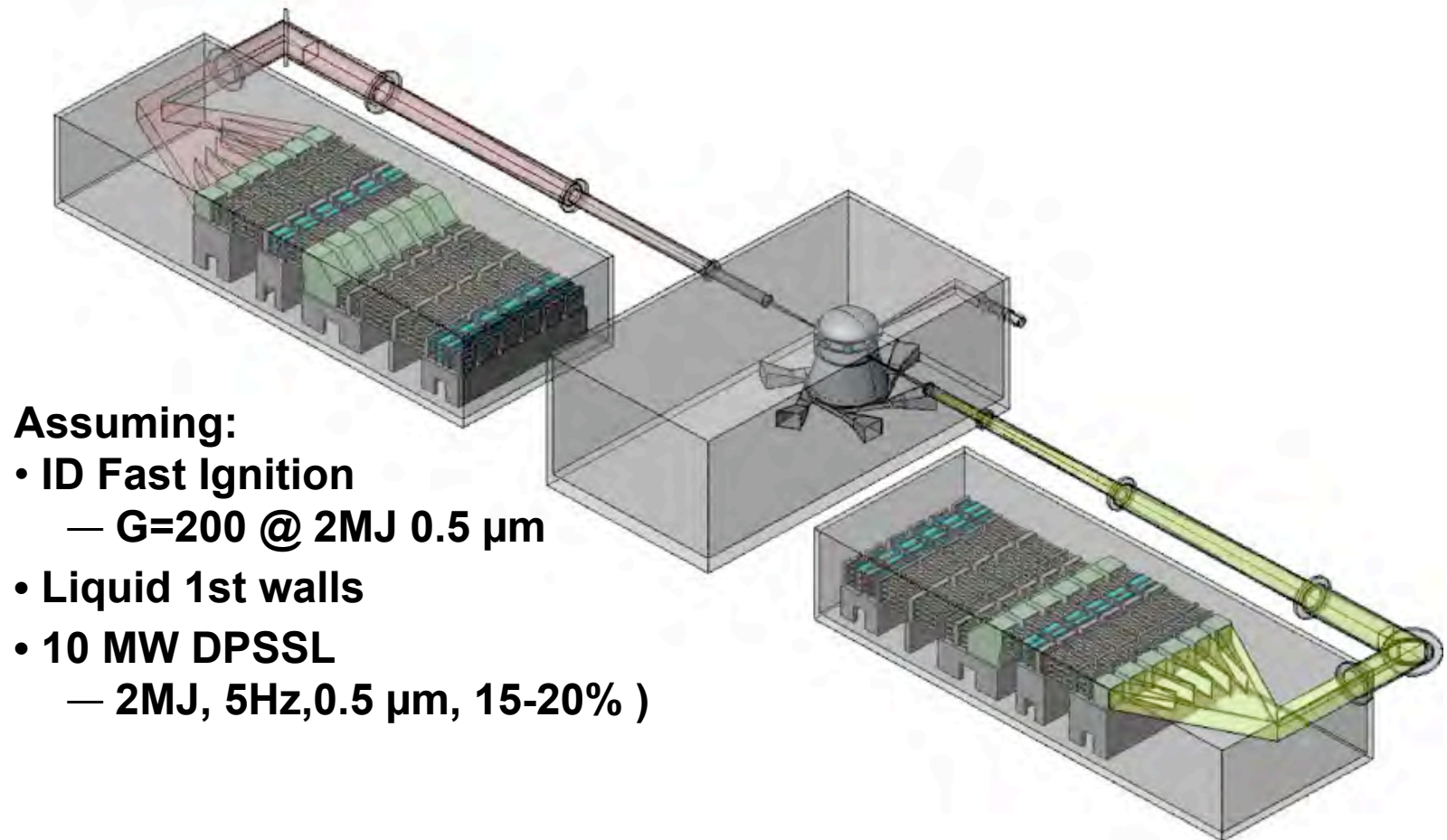
Inertial Fusion Energy (1960)



DOE NNSA

Challenges include making it safe, reliable, and cost effective

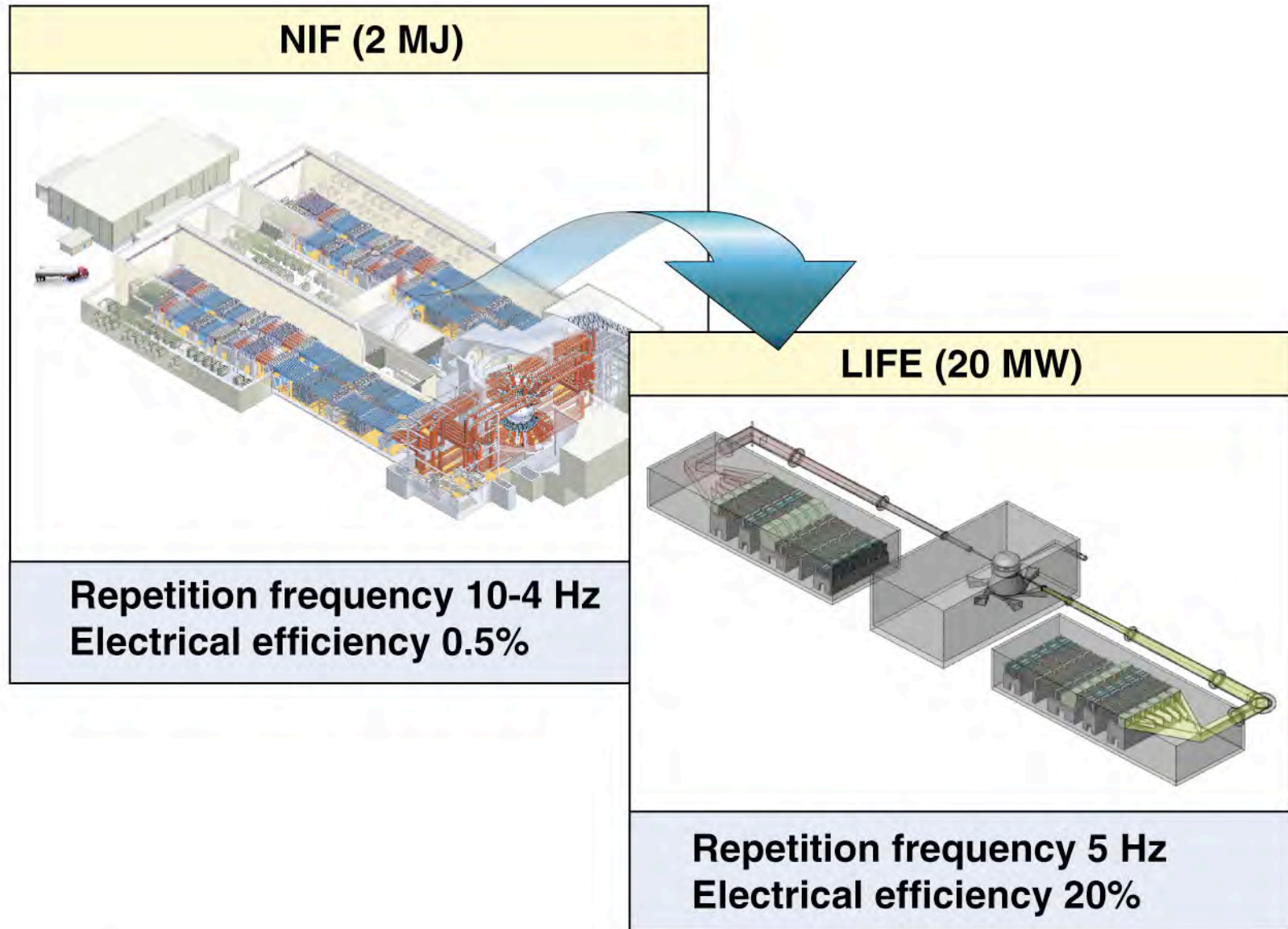
We have performed a systems study of a 1 GWe IFE power plant



Assuming:

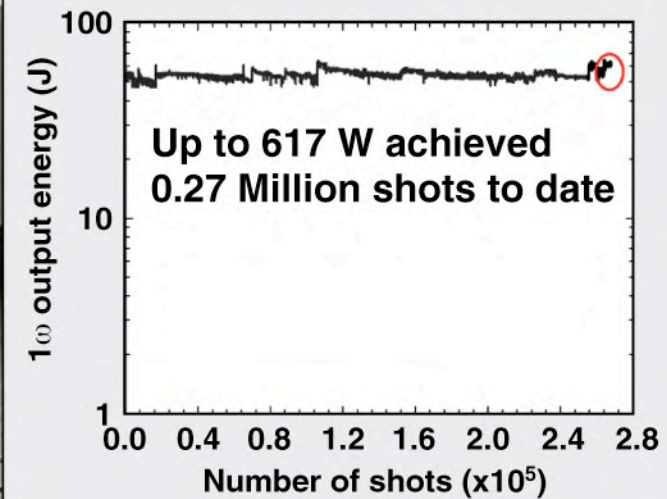
- ID Fast Ignition
 - $G=200$ @ 2MJ 0.5 μm
- Liquid 1st walls
- 10 MW DPSSL
 - 2MJ, 5Hz, 0.5 μm , 15-20%)

Is NIF a precursor to an Inertial Fusion Energy plant?

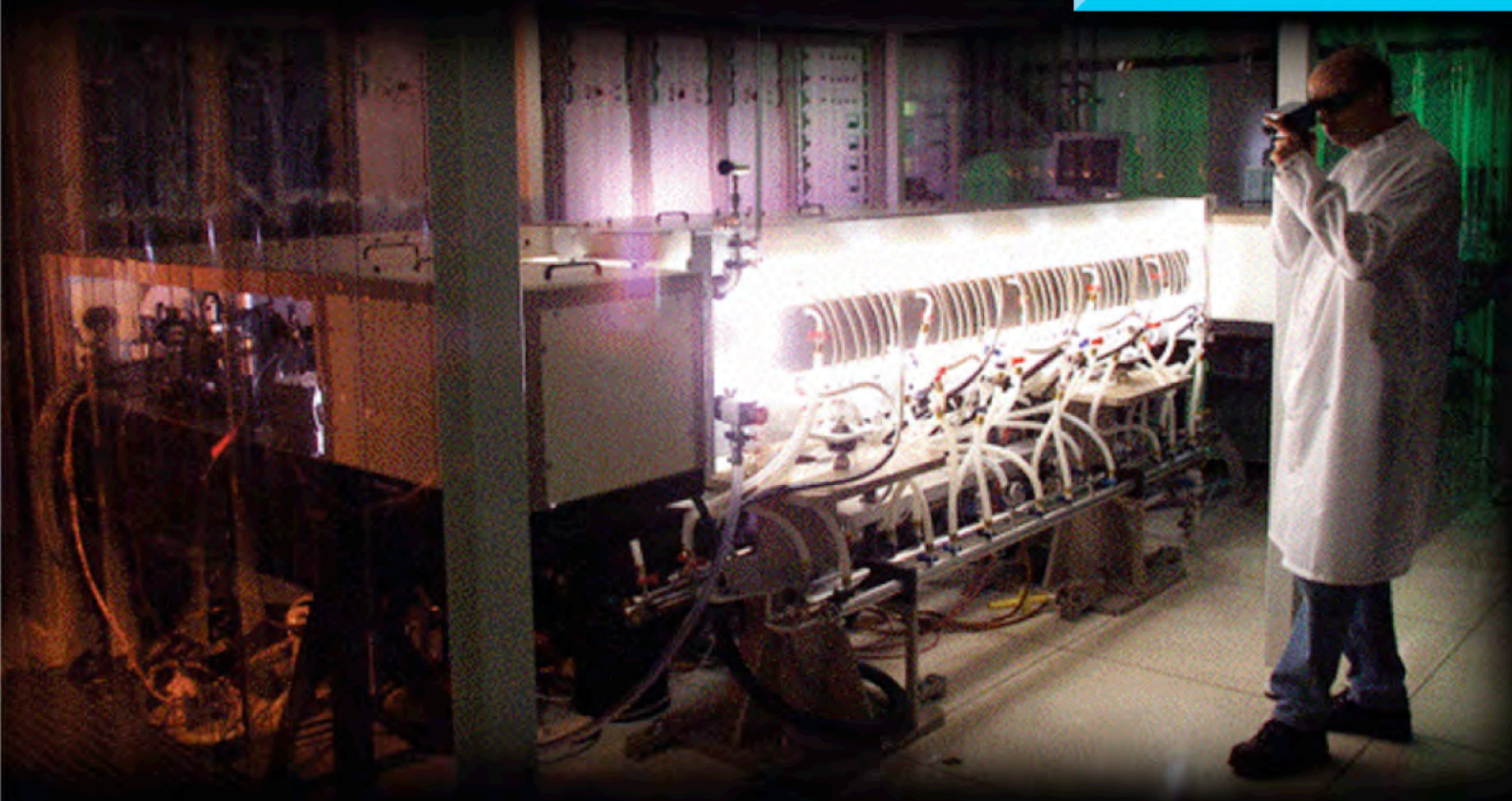


Mercury Laser at LLNL

- 40 W/cm²
- Scalable architecture
- 0.27 M shots to date



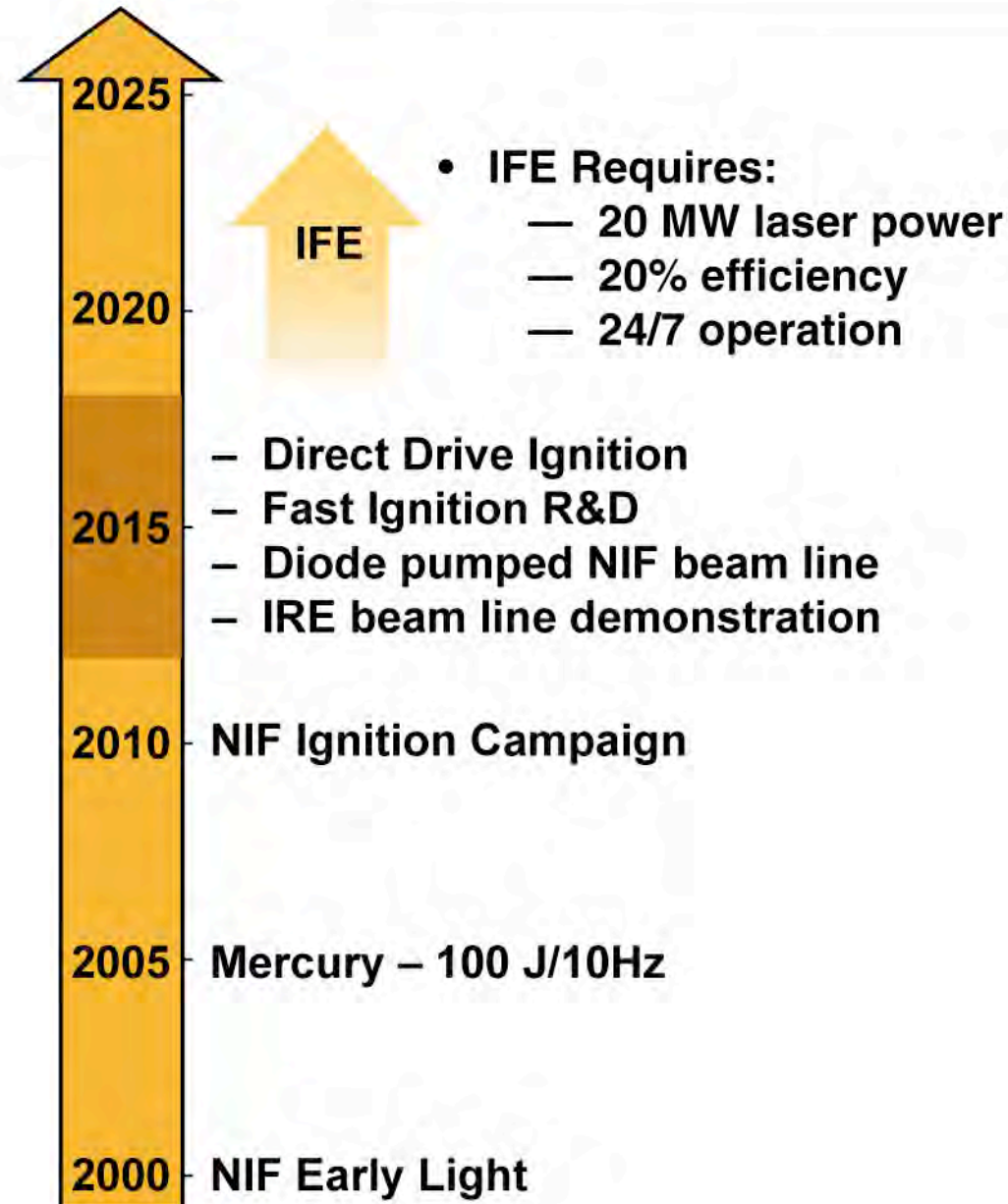
- LLNL/DOD 50 kW Heat Capacity Laser
- 10 x 10 ceramic Nd:YAG
 - 10 sec. burst mode operation
 - $> 250 \text{ W/cm}^2$



Leveraging the NIF provides a near-term pathway for fusion energy



The National Ignition Facility

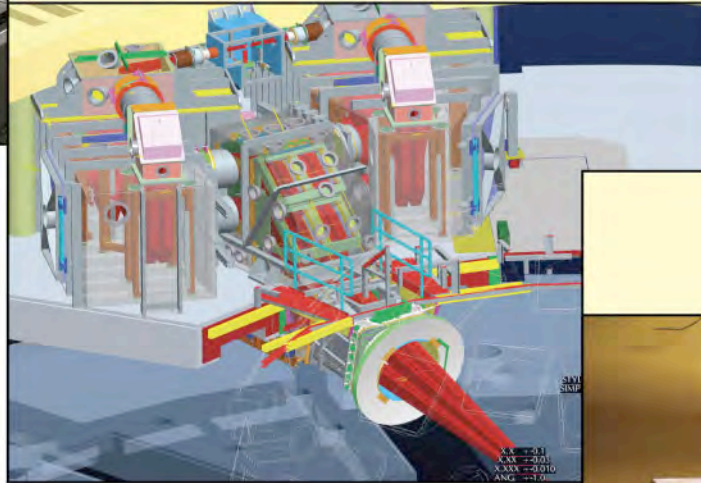


**Average Power:
kW to MW**

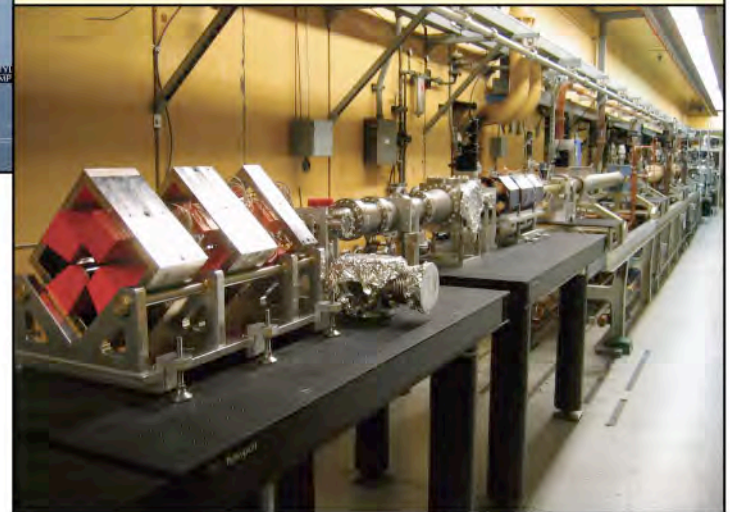


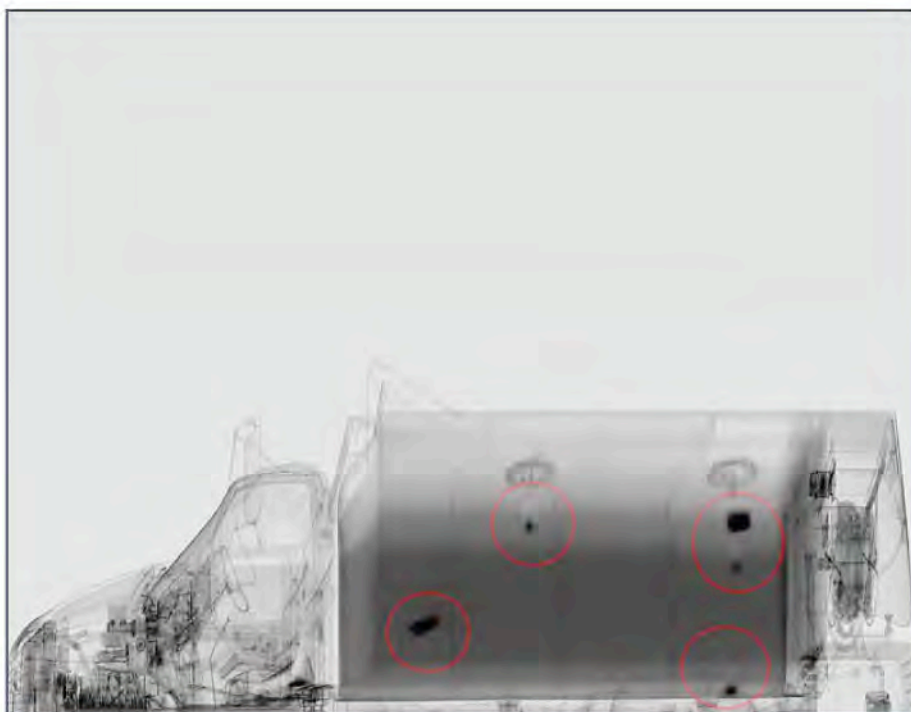
**PS&A is the
growth engine
for the
NIF Directorate**

**Peak Power:
Petawatts to Exawatts**



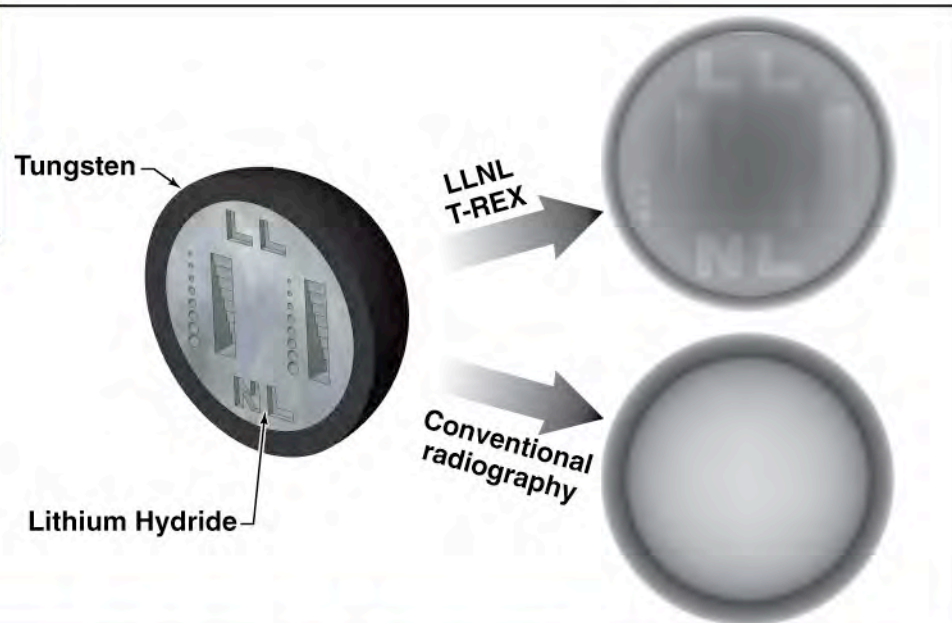
**Photon Energy:
keV to MeV**





Border Surveillance

**Laser based
gamma rays enable
isotope imaging**



**This capability is
transformational Photon
Science & Applications**

Stockpile Surveillance

NIF: Visions of yesterday become reality of today



The National Ignition Facility

1960's – Invention of Laser



2010 – Goal of Ignition

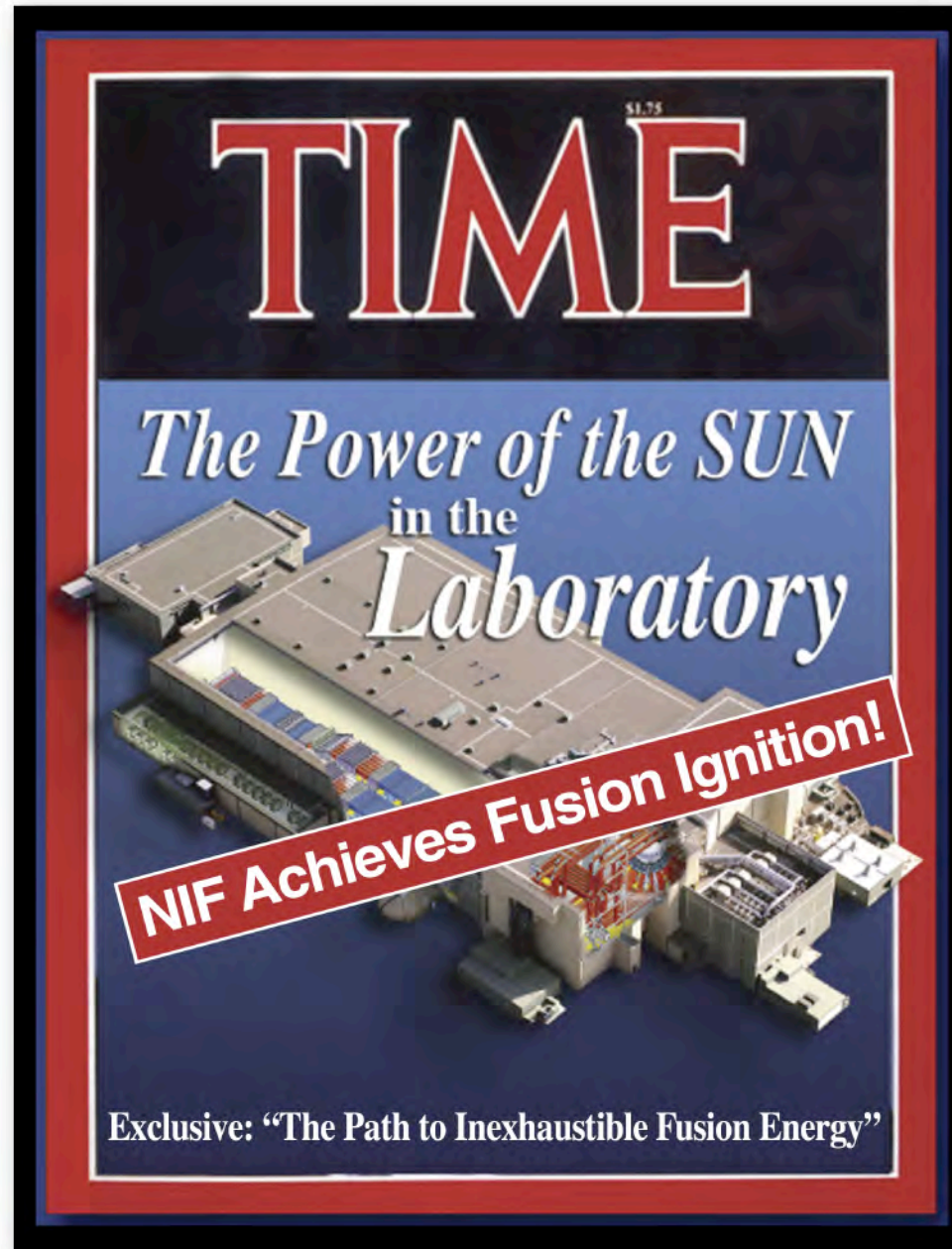


Ignition by 2010
Golden Anniversary of the Invention of the Laser
and the ICF Concept

A glimpse into the future



The National Ignition Facility



From the Sun to the Sun

Oct '03

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